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# Electrical Engineering

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HANDBOOK

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## D/A and A/D Converters

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an A. R. Garrod  
University

### 31.1 Integrated Circuits\*

*Digital-to-analog (D/A) conversion* is the process of converting digital codes into a continuous range of analog signal levels. *Analog-to-digital (A/D) conversion* is the process of converting a continuous range of analog signal levels into digital codes. Such conversion processes are necessary to interface real-world systems, which typically monitor continuously varying analog signals, with digital systems that process, store, interpret, and manipulate the analog values.

D/A and A/D conversion circuits are available as integrated circuits (ICs) from many manufacturers. A huge array of ICs exists, consisting of not only the D/A or A/D conversion circuits, but also closely related circuits such as sample-and-hold amplifiers, analog multiplexers, voltage-to-frequency and frequency-to-voltage converters, voltage references, calibrators, operation amplifiers, isolation amplifiers, instrumentation amplifiers, active filters, dc-to-dc converters, analog interfaces to digital signal processing systems, and data acquisition subsystems. Data books from the IC manufacturers contain an enormous amount of information about these devices and their applications to assist the design engineer.

The ICs discussed in this chapter will be strictly the D/A and A/D conversion circuits. Table 31.1 lists a small sample of the variety of the D/A and A/D converters currently available. The ICs usually perform either D/A or A/D conversion. There are serial interface ICs, however, typically for high-performance audio and digital signal processing applications, that perform both A/D and D/A processes.

### D/A and A/D Converter Performance Criteria

The major factors that determine the quality of performance of D/A and A/D converters are *resolution*, *sampling rate*, *speed*, and *linearity*.

The *resolution* of a D/A circuit is the smallest change in the output analog signal. In an A/D system, the resolution is the smallest change in voltage that can be detected by the system and that can

\*Excerpts from *Digital Logic: Analysis, Application and Design*, by Susan Garrod and Robert Borns, copyright © 1991 by Saunders College Publishing, reprinted by permission of the publisher. Material regarding the advanced technical details of the ICs has been taken from data books that are listed in the reference section at the end of this chapter.

Table 31.1 D/A and A/D Integrated Circuits

D/A Converter ICs				
IC	Resolution (bits)	Multiplying vs. Fixed Reference	Settling Time ( $\mu$ s)	Input Data Format
Analog Devices AD558	8	Fixed reference	3	Parallel
Analog Devices AD7524	8	Multiplying	0.400	Parallel
Analog Devices AD390	Quad, 12	Fixed reference	8	Parallel
Analog Devices AD1856	16	Fixed reference	1.5	Serial
Burr-Brown DAC729	18	Fixed reference	8	Parallel
DATel DAC-08B	8	Multiplying	0.085	Parallel
National DAC0800	8	Multiplying	0.1	Parallel
TI AD7533 or TLC7533	10	Multiplying	0.15	Parallel
A/D Converter ICs				
IC	Resolution (bits)	Signal Inputs	Conversion Speed ( $\mu$ s)	Output Data Format
Analog Devices AD572	12	1	25	Serial & parallel
Burr-Brown ADC804	12	1	17	Serial
Burr-Brown ADC700	16	1	17	Serial & parallel
DATel ADC-208	8	1	35	Parallel
DATel ADC-830	8	1	100	Parallel
National ADC1005B	10	1	50	Parallel
TI, National ADC0808	8	8	100	Parallel
TI, National ADC0834	8	4	84	Serial
TI TLC0820	8	1	1	Parallel
TI TLC1540	10	11	31	Serial
A/D and D/A Interface ICs				
IC	Resolution (bits)	On-Board Filters	Sampling Rate (kHz)	Data Format
TI TLC32040	14	Yes	19.2 (programmable)	Serial
TI 2914 PCM codec & filter	8	Yes	8	Serial

produce a change in the digital code. The resolution determines the total number of digital codes, or *quantization levels*, that will be recognized or produced by the circuit.

The *resolution* of a D/A or A/D IC is usually specified in terms of the bits in the digital code or in terms of the least significant bit (LSB) of the system. An  $n$ -bit code allows for  $2^n$  quantization levels, or  $2^n - 1$  steps between quantization levels, as shown in Fig. 31.1. As the number of bits increases, the step size between quantization levels decreases, therefore increasing the accuracy of the system when a conversion is made between an analog and digital signal. The system resolution can be specified also as the voltage step size between quantization levels. For A/D circuits, the resolution is the smallest input voltage that is detected by the system.

The *speed* of a D/A or A/D converter is determined by the time it takes to perform the conversion process. For D/A converters, the speed is specified as the *settling time*. For A/D converters, the speed is specified as the *conversion time*. The settling time for D/A converters will vary with supply voltage and transition in the digital code; thus, it is specified in the data sheet with the appropriate conditions stated.

A/D converters have a maximum *sampling rate* that limits the speed at which they can perform continuous conversions. The sampling rate is the number of times per second that the analog signal can be sampled and converted into a digital code. For proper A/D conversion, the minimum sampling rate must be at least two times the highest frequency of the analog signal being sampled to satisfy the Nyquist sampling criterion. The conversion speed and other timing factors must be taken into consideration to determine the maximum sampling rate of an A/D converter. Nyquist A/D converters use a sampling rate that is slightly more than twice the highest frequency in the analog signal. Oversampling A/D converters use sampling rates of  $N$  times this rate, where  $N$  typically ranges from 2 to 64.

## Input Data Format

Parallel  
Parallel  
Parallel  
Serial  
Parallel  
Parallel  
Parallel  
Parallel

## Output Data Format

Serial & parallel  
Serial  
Serial & parallel  
Parallel  
Parallel  
Parallel  
Parallel  
Serial  
Parallel  
Serial

(Hz) Data Format

(ble) Serial  
Serial

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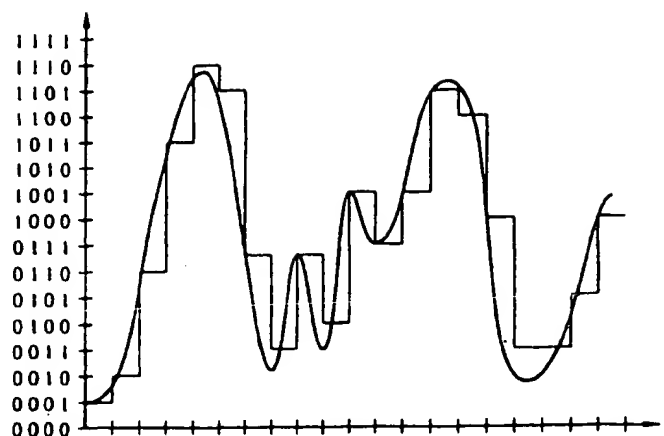


FIGURE 31.1 A/D conversion—4-bit resolution. (Source: *Digital Logic: Analysis, Application, and Design* by Susan Garrod and Robert Borns, copyright © 1991 by Saunders College Publishing, p. 893. Reprinted by permission of the publisher.)

Both D/A and A/D converters require a voltage reference in order to achieve absolute measurement accuracy. Some conversion ICs have internal voltage references, while others accept external voltage references. For high-performance systems, an external precision reference is needed to ensure long-term stability, load regulation, and control over temperature fluctuations. External precision voltage reference ICs can be found in manufacturers' data books.

Measurement accuracy is specified by the converter's *linearity*. *Integral linearity* is a measure of linearity over the entire conversion range. It is often defined as the deviation from a straight line drawn between the endpoints and through zero (or the offset value) of the conversion range. Integral linearity is also referred to as *relative accuracy*. The *offset* value is the reference level required to establish the zero or midpoint of the conversion range. *Differential linearity* is the linearity between code transitions. Differential linearity is a measure of the *monotonicity* of the converter. A converter is said to be monotonic if increasing input values result in increasing output values.

The accuracy and linearity values of a converter are specified in the data sheet in units of the LSB of the code. The linearity can vary with temperature, so the values are often specified at +25°C as well as over the entire temperature range of the device.

## D/A Conversion Processes

Digital codes are typically converted to analog voltages by assigning a voltage weight to each bit in the digital code and then summing the voltage weights of the entire code. A general D/A converter consists of a network of precision resistors, input switches, and level shifters to activate the switches to convert a digital code to an analog current or voltage. D/A ICs that produce an analog current output usually have a faster settling time and better linearity than those that produce a voltage output. When the output current is available, the designer can convert this to a voltage through the selection of an appropriate output amplifier to achieve the necessary response speed for the given application.

D/A converters commonly have a fixed or variable reference level. The reference level determines the switching threshold of the precision switches that form a controlled impedance network, which in turn controls the value of the output signal. **Fixed reference D/A converters** produce an output signal that is proportional to the digital input. **Multiplying D/A converters** produce an output signal that is proportional to the product of a varying reference level times a digital code.

D/A converters can produce bipolar, positive, or negative polarity signals. A four-quadrant multiplying D/A converter allows both the reference signal and the value of the binary code to have a positive or negative polarity. The four-quadrant multiplying D/A converter produces bipolar output signals.

### D/A Converter ICs

Most D/A converters are designed for general-purpose data acquisition applications. Some D/A converters, however, are designed for special applications, such as video or graphic outputs, high-definition video displays, ultra high-speed signal processing, digital video tape recording, digital attenuators, or high-speed function generators.

D/A converter ICs often include special features that enable them to be interfaced easily to microprocessors or other systems. Microprocessor control inputs, input latches, buffers, input registers, and compatibility to standard logic families are features that are readily available in D/A ICs. In addition, the ICs usually have laser-trimmed precision resistors to eliminate the need for user trimming to achieve full-scale performance.

A small sample of specific D/A converter ICs will be discussed in this section to illustrate their operation. Numerous D/A converter ICs exist for D/A applications that should be investigated by examining the data books published by the IC manufacturers.

#### AD558 D/A Converter by Analog Devices

The AD558 is a fixed reference D/A converter by Analog Devices that produces an output voltage proportional to the digital input code. The output voltage is calibrated over two voltage ranges: 0 to 2.56 V and 0 to 10.00 V. The functional block diagram for the AD558 is shown in Fig. 31.2.

The AD558 is an 8-bit D/A converter. The functions shown in the block diagram in Fig. 31.2 enable the AD558 to be interfaced directly to microprocessors or other circuitry, because of its input latches, control signals, internal precision voltage reference, and output amplifier. The input latches for the digital code can be controlled for microprocessor interfacing to accept a new digital code or to latch the given digital code, or they can be disabled for direct D/A conversion interfacing.

The AD558 is designed to operate with a single power supply of +4.5 to +16.5 V. The output voltage range is unipolar, from 0 to +2.56 V or from 0 to +10 V, depending on the power supply and output amplifier configuration.

The output settling time varies with the output voltage range, the output load, and whether the

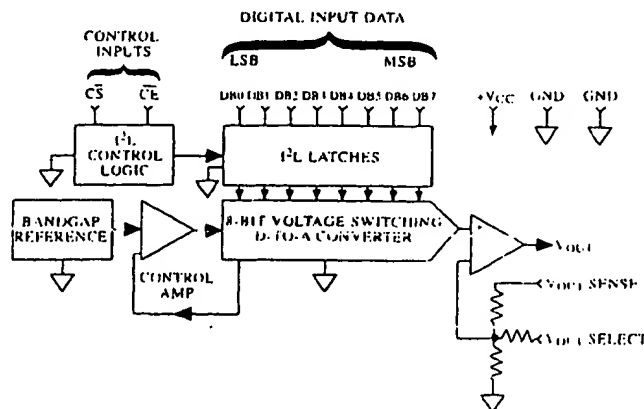


FIGURE 31.2 D/A converter: AD558 functional block diagram.

(Source: AD558 D/A Converter Data Sheet, *Analog Devices Data Conversion Products Databook*, Analog Devices, Inc., Norwood, Mass., 1989/90, p. 2-50. With permission.)

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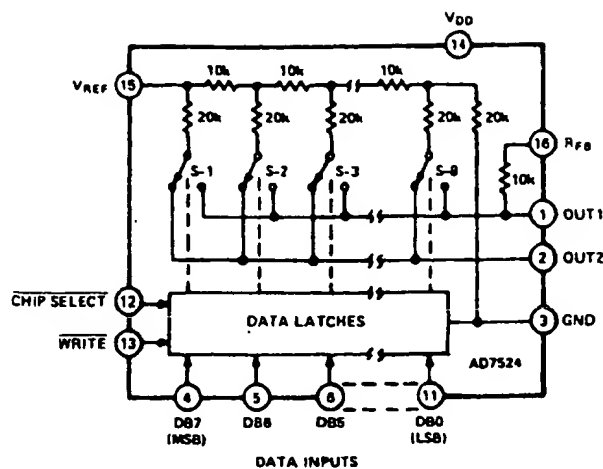


FIGURE 31.3 D/A converter: AD7524 functional block diagram.  
(Source: AD7524 D/A Converter Data Sheet, *Analog Devices Data Conversion Products Databook*, Analog Devices, Inc., Norwood, Mass., 1989/90, p. 2-235. With permission.)

output is positive-going or negative-going. For a positive-going full-scale to  $\pm$ LSB output, the maximum settling time is 1.5  $\mu$ s for the 2.56-V output range and 3  $\mu$ s for the 10-V output range.

Relative accuracy varies from  $\pm 0.25$  to  $\pm 0.75$  LSB, depending on the temperature range and laser trimming of the device. Full-scale accuracy is  $\pm 1.5$  LSB at  $+25^\circ\text{C}$  and  $\pm 2.5$  LSB over the entire temperature range. The AD558 is available in packages rated for performance over a temperature range of 0 to  $+70^\circ\text{C}$  or the range  $-55$  to  $+125^\circ\text{C}$ .

#### AD7524 D/A Converter by Analog Devices

The AD7524 varying reference D/A converter IC by Analog Devices produces an output current that is a product of the 8-bit digital input code and an input reference voltage. The functional block diagram for the AD7524 is shown in Fig. 31.3. The AD7524 is capable of 2- or 4-quadrant multiplication when the reference voltage is varied.

As shown in Fig. 31.3, the AD7524 consists of an R/2R resistor ladder, data latches, and microprocessor interface logic. The AD7524 is often used with a voltage reference and an output amplifier to produce an output voltage. The manufacturer recommends this circuit for general-purpose microprocessor-controlled applications such as function generators, attenuators, and precision automatic gain control circuits.

The AD7524 is designed to operate with a power supply of  $\pm 4.5$  to  $\pm 18$  V. The output can be unipolar or bipolar, depending on the output amplifier configuration, as shown in Fig. 31.4. The output settling time varies with the input reference voltage, digital code transition, and output load. The maximum settling time, with a  $V_{DD}$  of +5 V, is 400 ns for 0.5 LSB accuracy over the full scale.

#### A/D Conversion Processes

Analog signals can be converted to digital codes by many methods, including integration, successive approximation, parallel (flash) conversion, delta modulation, pulse code modulation, and sigma-delta conversion. Two of the most common A/D conversion processes are successive approximation A/D conversion and parallel or flash A/D conversion. Very high-resolution digital audio or video systems require specialized A/D techniques that often incorporate one of these general techniques as well as specialized A/D conversion processes. Examples of specialized A/D conversion techniques are

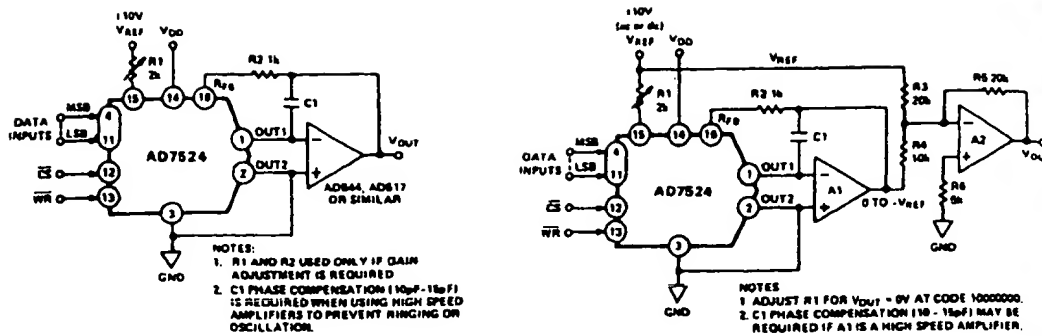


FIGURE 31.4 D/A converter: AD7524 unipolar and bipolar operation, circuit configurations. (Source: AD7524 D/A Converter Data Sheet, Analog Devices Data Conversion Products Databook, Analog Devices, Inc., Norwood, Mass., 1989/90, p. 2-239. With permission.)

pulse code modulation (PCM), and sigma-delta conversion. PCM is a common voice encoding scheme used not only by the audio industry in digital audio recordings but also by the telecommunications industry for voice encoding and multiplexing. Sigma-delta conversion is an oversampling A/D conversion where signals are sampled at very high frequencies. It has very high resolution and low distortion and is being used in the digital audio recording industry.

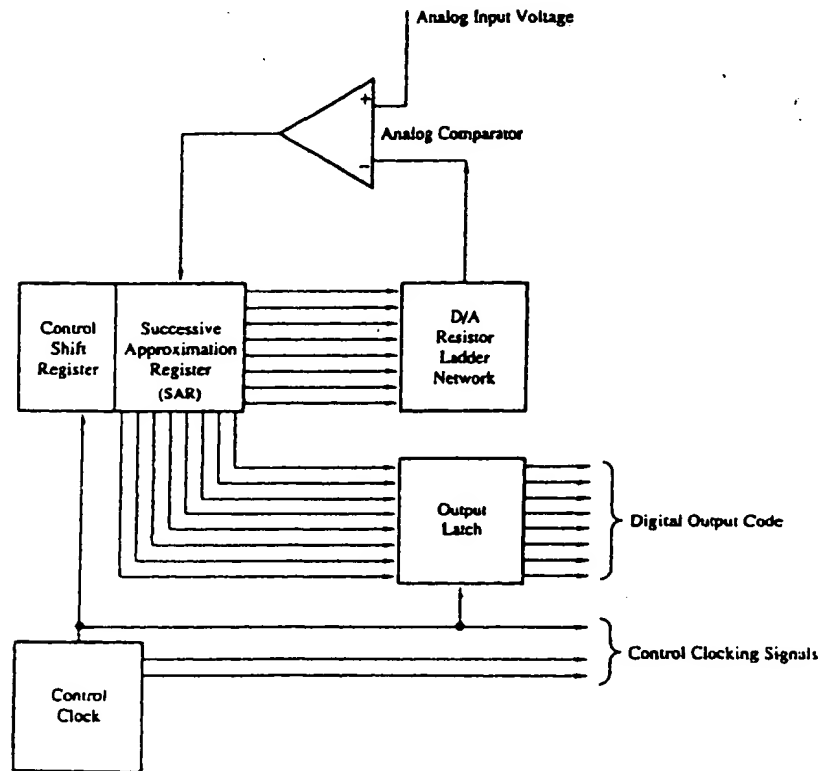
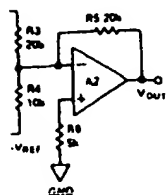


FIGURE 31.5 Successive approximation A/D converter block diagram. (Source: *Digital Logic: Analysis, Application, and Design* by Susan Garrod and Robert Borne, copyright © 1991 by Saunders College Publishing, p. 919. Reprinted by permission of the publisher.)



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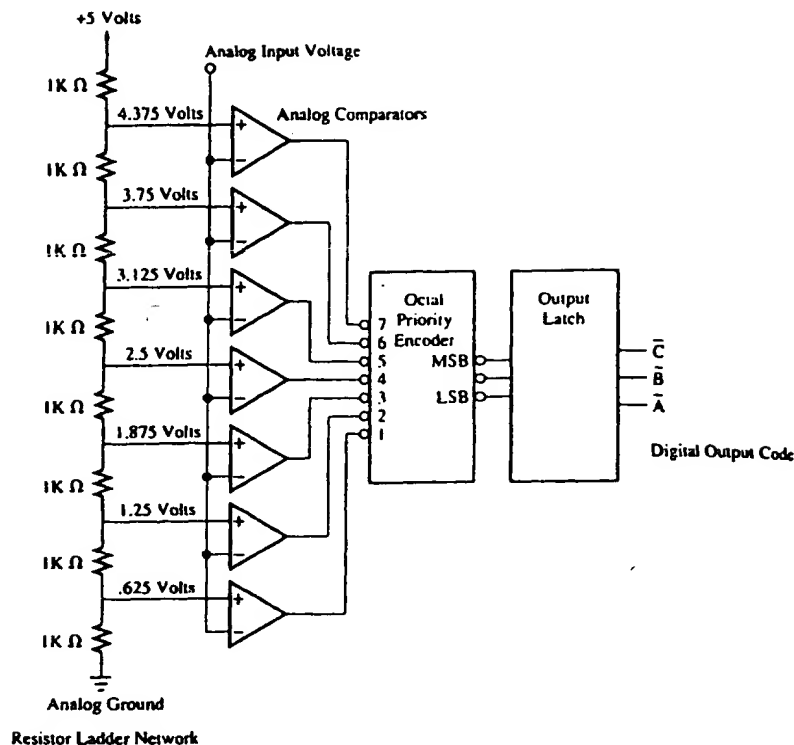


FIGURE 31.6 Flash A/D converter block diagram. (Source: *Digital Logic: Analysis, Application, and Design* by Susan Garrod and Robert Borns, copyright © 1991 by Saunders College Publishing, p. 928. Reprinted by permission of the publisher.)

Successive approximation A/D conversion is a technique that is commonly used in medium- to high-speed data acquisition applications. It is one of the fastest A/D conversion techniques that requires a minimum amount of circuitry. The conversion times for successive approximation A/D conversion typically range from 10 to 300  $\mu$ s for 8-bit systems.

The successive approximation A/D converter can approximate the analog signal to form an  $n$ -bit digital code in  $n$  steps. The successive approximation register (SAR) individually compares an analog input voltage to the midpoint of one of  $n$  ranges to determine the value of one bit. This process is repeated a total of  $n$  times, using  $n$  ranges, to determine the  $n$  bits in the code. The comparison is accomplished as follows: The SAR determines if the analog input is above or below the midpoint and sets the bit of the digital code accordingly. The SAR assigns the bits beginning with the most significant bit. The bit is set to a 1 if the analog input is greater than the midpoint voltage, or it is set to a 0 if it is less than the midpoint voltage. The SAR then moves to the next bit and sets it to a 1 or a 0 based on the results of comparing the analog input with the midpoint of the next allowed range. Because the SAR must perform one approximation for each bit in the digital code, an  $n$ -bit code requires  $n$  approximations.

A successive approximation A/D converter consists of four functional blocks, as shown in Fig. 31.5: the SAR, the analog comparator, a D/A converter, and a clock.

Parallel or flash A/D conversion is used in high-speed applications such as video signal processing, medical imaging, and radar detection systems. A flash A/D converter simultaneously compares the input analog voltage to  $2^n - 1$  threshold voltages to produce an  $n$ -bit digital code representing the analog voltage. Typical flash A/D converters with 8-bit resolution operate at 20 to 100 MHz.

The functional blocks of a flash A/D converter are shown in Fig. 31.6. The circuitry consists of a

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precision resistor ladder network,  $2^n - 1$  analog comparators, and a digital priority encoder. The resistor network establishes threshold voltages for each allowed quantization level. The analog comparators indicate whether or not the input analog voltage is above or below the threshold at each level. The output of the analog comparators is input to the digital priority encoder. The priority encoder produces the final digital output code that is stored in an output latch.

An 8-bit flash A/D converter requires 255 comparators. The cost of high-resolution A/D converters escalates as the circuit complexity increases and as the number of analog converters rises by  $2^n - 1$ . As a low-cost alternative, some manufacturers produce modified flash A/D converters that perform the A/D conversion in two steps to reduce the amount of circuitry required. These modified flash A/D converters are also referred to as *half-flash* A/D converters, since they perform only half of the conversion simultaneously.

### A/D Converter ICs

A/D converter ICs can be classified as general-purpose, high-speed, flash, and sampling A/D converters. The *general-purpose A/D converters* are typically low speed and low cost, with conversion times ranging from 2  $\mu$ s to 33 ms. A/D conversion techniques used by these devices typically include successive approximation, tracking, and integrating. The general-purpose A/D converters often have control signals for simplified microprocessor interfacing. These ICs are appropriate for many process control, industrial, and instrumentation applications, as well as for environmental monitoring such as seismology, oceanography, meteorology, and pollution monitoring.

*High-speed A/D converters* have conversion times typically ranging from 400 ns to 3  $\mu$ s. The higher speed performance of these devices is achieved by using the successive approximation technique, modified flash techniques, and statistically derived A/D conversion techniques. Applications appropriate for these A/D ICs include fast Fourier transform (FFT) analysis, radar digitization, medical instrumentation, and multiplexed data acquisition. Some ICs have been manufactured with an extremely high degree of linearity, to be appropriate for specialized applications in digital spectrum analysis, vibration analysis, geological research, sonar digitizing, and medical imaging.

*Flash A/D converters* have conversion times ranging typically from 10 to 50 ns. Flash A/D conversion techniques enable these ICs to be used in many specialized high-speed data acquisition applications such as TV video digitizing (encoding), radar analysis, transient analysis, high-speed digital oscilloscopes, medical ultrasound imaging, high-energy physics, and robotic vision applications.

*Sampling A/D converters* have a sample-and-hold amplifier circuit built into the IC. This eliminates the need for an external sample-and-hold circuit. The throughput of these A/D converter ICs ranges typically from 35 kHz to 100 MHz. The speed of the system is dependent on the A/D technique used by the sampling A/D converter.

A/D converter ICs produce digital codes in a serial or parallel format, and some ICs offer the designer both formats. The digital outputs are compatible with standard logic families to facilitate interfacing to other digital systems. In addition, some A/D converter ICs have a built-in analog multiplexer and therefore can accept more than one analog input signal.

*Pulse code modulation (PCM) ICs* are high-precision A/D converters. The PCM IC is often referred to as a PCM *codec* with both encoder and decoder functions. The encoder portion of the codec performs the A/D conversion, and the decoder portion of the codec performs the D/A conversion. The digital code is usually formatted as a serial data stream for ease of interfacing to digital transmission and multiplexing systems.

PCM is a technique where an analog signal is sampled, quantized, and then encoded as a digital word. The PCM IC can include successive approximation techniques or other techniques to accomplish the PCM encoding. In addition, the PCM codec may employ nonlinear data compression techniques, such as companding, if it is necessary to minimize the number of bits in the output digital code. Companding is a logarithmic technique used to compress a code to fewer bits before transmission. The inverse logarithmic function is then used to expand the code to its origi-

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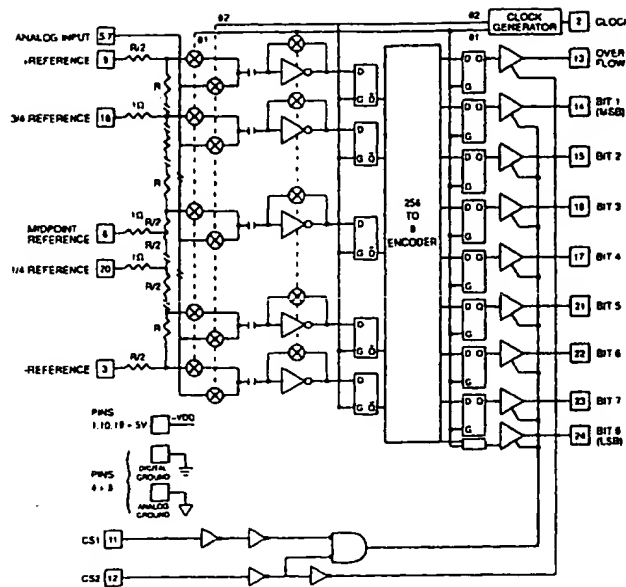


FIGURE 31.7 Flash A/D converter: ADC-208 simplified block diagram. (Source: ADC-208 A/D Converter Data Sheet, DATEL Data Conversion Catalog, DATEL, Inc., Mansfield, Mass., 1988, p. 1-11. With permission)

nal number of bits before converting it to the analog signal. Companding is typically used in telecommunications transmission systems to minimize data transmission rates without degrading the resolution of low-amplitude signals. Linear PCM conversion is used in high-fidelity audio systems to preserve the integrity of the audio signal throughout the entire analog range.

Digital signal processing (DSP) techniques provide another type of A/D conversion ICs. Specialized A/D conversion such as *adaptive differential pulse code modulation (ADPCM)*, *sigma-delta modulation*, *speech subband encoding*, *adaptive predictive speech encoding*, and *speech recognition* can be accomplished through the use of DSP systems. Some DSP systems require analog front ends that employ traditional PCM codec ICs or DSP interface ICs. These ICs can interface to a digital signal processor for advanced A/D applications. Some manufacturers have incorporated DSP techniques on board the single-chip A/D IC, as in the case of the DSP56ACD16 sigma-delta modulation IC by Motorola.

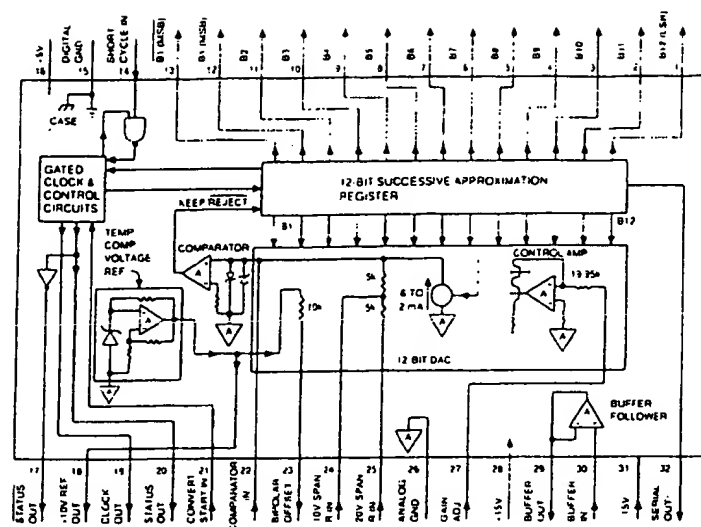
A small sample of specific A/D converter ICs will be discussed in this section to illustrate their operation. As was the case with D/A converters, numerous A/D converter ICs exist that should be investigated for the specific A/D application in question.

#### ADC-208 Flash A/D Converter by DATEL

The ADC-208 is an 8-bit flash A/D converter. The simplified block diagram for the ADC-208 is shown in Fig. 31.7. The ADC-208 consists of 256 comparators that perform the parallel or flash conversion of the analog input signal. The output data are available in three-state output latches with an overflow detection indicator.

The ADC-208 has a switched capacitor input stage, and therefore its input impedance is dependent on its sampling frequency. It is recommended by the manufacturer that an external input buffer be used because of this varying input impedance.

The ADC-208 is designed to operate with a single power supply of +5 V. The allowed analog input voltage range is 0 to +5 V. The sampling rate of the ADC-208 is 20 mega samples per second. The full



**FIGURE 31.8** Successive approximation A/D converter: AD572 functional block diagram. (Source: AD572 A/D Converter Data Sheet, *Analog Devices Data Conversion Products Databook*, Analog Devices, Inc., Norwood, Mass., 1989/90, p. 3-21. With permission.)

power bandwidth is 10 MHz, adhering to the Nyquist sampling criteria. The integral linearity is  $\pm 0.5$  LSB between endpoints at  $\pm 25^\circ\text{C}$  and  $\pm 1$  LSB over the temperature range. Differential linearity is  $\pm 0.75$  LSB between code transitions at  $\pm 25^\circ\text{C}$  and  $\pm 1$  LSB over the temperature range.

The digital output is a straight binary 8-bit code. The code range is adjustable over a voltage range defined by the positive and negative reference voltage inputs. Two ADC-208s can be cascaded to achieve 9-bit resolution over the defined voltage range.

#### AD571 Successive Approximation A/D Converter by Analog Devices

The AD572 is a 12-bit A/D converter that uses the successive approximation method for conversion. The functional block diagram of the AD572 is shown in Fig. 31.8. The output data are available in both a serial and parallel format.

The AD572 12-bit successive approximation A/D converter has an internal clock, a  $+10\text{-V}$  voltage reference, and an input buffer amplifier. Analog scaling resistors enable the AD572 to be operated for analog input ranges of  $\pm 2.5\text{ V}$ ,  $\pm 5.0\text{ V}$ ,  $\pm 10\text{ V}$ ,  $0$  to  $+5\text{ V}$ , or  $0$  to  $+10\text{ V}$ . The internal  $+10\text{-V}$  precision voltage reference can be used for external applications. The AD572 requires a  $\pm 15\text{-V}$  and  $+5\text{-V}$  power supply.

The AD572 requires a conversion time of  $25\text{ }\mu\text{s}$ . The internal clock has a maximum output frequency of  $500\text{ kHz}$ . Thirteen clock cycles are required for each conversion.

The maximum linearity error is  $0.012\%$  of full scale. The differential linearity error is  $\pm 0.5$  LSB. The unipolar offset error is  $\pm 0.05\%$  of full scale, and the bipolar offset error is  $\pm 0.1\%$  of full scale. A sample-and-hold amplifier is recommended for use between the analog source and the input to the AD572 if the input voltage can change by more than  $0.5$  LSB during a conversion.

#### Grounding and Bypassing on D/A and A/D ICs

D/A and A/D converter ICs require correct grounding and capacitive bypassing in order to operate according to performance specifications. The digital signals can severely impair analog signals. To combat the electromagnetic interference induced by the digital signals, the analog and digital

Defin

grounds should be kept separate and should have only one common point on the circuit board. If possible, this common point should be the connection to the power supply.

Bypass capacitors are required at the power connections to the IC, the reference signal inputs, and the analog inputs to minimize noise that is induced by the digital signals. Each manufacturer specifies the recommended bypass capacitor locations and values in the data sheet. The 1- $\mu$ F tantalum capacitors are commonly recommended, with additional high-frequency power supply decoupling sometimes being recommended through the use of ceramic disc shunt capacitors. The manufacturers' recommendations should be followed to ensure proper performance.

### Selection Criteria for D/A and A/D Converter ICs

Hundreds of D/A and A/D converter ICs are available, with prices ranging from a few dollars to several hundred dollars each. The selection of the appropriate type of converter is based on the application requirements of the system, the performance requirements, and cost. The following issues should be considered in order to select the appropriate converter.

1. What are the input and output requirements of the system? Specify all signal current and voltage ranges, logic levels, input and output impedances, digital codes, data rates, and data formats.
2. What level of accuracy is required? Determine the resolution needed throughout the analog voltage range, the dynamic response, the degree of linearity, and the number of bits encoding.
3. What speed is required? Determine the maximum analog input frequency for sampling in an A/D system, the number of bits for encoding each analog signal, and the rate of change of input digital codes in a D/A system.
4. What is the operating environment of the system? Obtain information on the temperature range and power supply to select a converter that is accurate over the operating range.

Final selection of D/A and A/D converter ICs should be made by consulting manufacturers to obtain their technical specifications of the devices. Major manufacturers of D/A and A/D converters include Analog Devices, Burr-Brown, DATFL, Maxim, National, Phillips Components, Precision Monolithics, Signetics, Sony, Texas Instruments, Ultra Analog, and Yamaha. Information on contacting these manufacturers and others can be found in an *IC Master Catalog*.

### Defining Terms

**Delta modulation:** An A/D conversion process where the digital code out represents the change or slope of the analog input signal, rather than the absolute value of the analog input signal. A 1 indicates a rising slope of the input signal. A 0 indicates a falling slope of the input signal. The sampling rate is dependent on the derivative of the signal, since a rapidly changing signal would require a rapid sampling rate for acceptable performance.

**Fixed reference D/A converter:** The analog output is proportional to a fixed (nonvarying) reference signal.

**Flash A/D:** The fastest A/D conversion process available to date, also referred to as parallel A/D conversion. The analog signal is simultaneously evaluated by  $2^n - 1$  comparators to produce an  $n$ -bit digital code in one step. Because of the large number of comparators required, the circuits for flash A/D converters can be very expensive. This technique is commonly used in digital video systems.

**Integrating A/D:** The analog input signal is integrated over time to produce a digital signal that represents the area under the curve, or the integral.

**Multiplying D/A:** A D/A conversion process where the output signal is the product of a digital code multiplied times an analog input reference signal. This allows the analog reference signal to be scaled by a digital code.

**Nyquist A/D converters:** A/D converters that sample analog signals that have a maximum frequency that is less than the Nyquist frequency. The Nyquist frequency is defined as one-half of the sampling frequency. If a signal has frequencies above the Nyquist frequency, a distortion called *aliasing* occurs. To prevent aliasing, an *antialiasing filter* with a flat passband and very sharp roll-off is required.

**Oversampling converters:** A/D converters that sample frequencies at a rate much higher than the Nyquist frequency. Typical oversampling rates are 32 and 64 times the sampling rate that would be required with the Nyquist converters.

**Pulse code modulation (PCM):** An A/D conversion process requiring three steps: the analog signal is sampled, quantized, and encoded into a fixed length digital code. This technique is used in many digital voice and audio systems. The reverse process reconstructs an analog signal from the PCM code.

**Sigma-delta A/D conversion:** An *oversampling* A/D conversion process where the analog signal is sampled at rates much higher (typically 64 times) than the sampling rates that would be required with a Nyquist converter. Sigma-delta modulators integrate the analog signal before performing the delta modulation. The integral of the analog signal is encoded rather than the change in the analog signal, as is the case for traditional delta modulation. A digital sample rate reduction filter (also called a digital decimation filter) is used to provide an output sampling rate at twice the Nyquist frequency of the signal. The overall result of oversampling and digital sample rate reduction is greater resolution and less distortion compared to a Nyquist converter process.

**Successive approximation:** An A/D conversion process that systematically evaluates the analog signal in  $n$  steps to produce an  $n$ -bit digital code. The analog signal is successively compared to determine the digital code, beginning with the determination of the most significant bit of the code.

## References

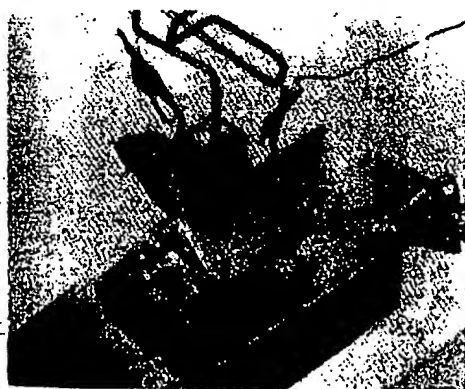
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- Texas Instruments Linear Circuits Data Acquisition and Conversion Data Book*, Texas Instruments, Dallas, Texas, 1989.

## Further Information

Analog Devices, Inc. has edited or published several technical handbooks to assist design engineers with their data acquisition system requirements. These references should be consulted for extensive technical information and depth. The publications include *Analog-Digital Conversion Handbook*, by the engineering staff of Analog Devices, published by Prentice-Hall, Englewood Cliffs, N.J.

1986; *Nonlinear Circuits Handbook*, *Transducer Interfacing Handbook*, and *Synchro and Resolver Conversion*, all published by Analog Devices Inc., Norwood, Mass.

Engineering trade journals and design publications often have articles describing recent A/D and D/A circuits and their applications. These publications include *EDN Magazine*, *EE Times*, and *IEEE Spectrum*.



The first transistors assembled by their inventors at Bell Laboratories (in 1947) were primitive by today's standards. Yet they revolutionized the electronics industry and changed our way of life. The first transistor, a "point-contact" type, amplified electrical signals by passing them through a solid semiconductor material, basically the same operation as performed by present "junction" transistors. The three terminal wires can be seen on the top of the transistor. The actual record of the first transistor operation was December 23, 1947. (Courtesy of Bell Telephone Laboratories.)

# 802.3®

IEEE Standard for  
Information technology—

Telecommunications and information  
exchange between systems—

Local and metropolitan area networks—

Specific requirements

**Part 3: Carrier sense multiple access with  
collision detection (CSMA/CD) access  
method and physical layer specifications**

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## 40. Physical Coding Sublayer (PCS), Physical Medium Attachment (PMA) sublayer and baseband medium, type 1000BASE-T

### 40.1 Overview

The 1000BASE-T PHY is one of the Gigabit Ethernet family of high-speed CSMA/CD network specifications. The 1000BASE-T Physical Coding Sublayer (PCS), Physical Medium Attachment (PMA) and baseband medium specifications are intended for users who want 1000 Mb/s performance over Category 5 balanced twisted-pair cabling systems. 1000BASE-T signaling requires four pairs of Category 5 balanced cabling, as specified in ISO/IEC 11801:1995 and ANSI/EIA/TIA-568-A (1995) and tested for the additional performance parameters specified in 40.7 using testing procedures defined in proposed ANSI/TIA/EIA TSB95.

This clause defines the type 1000BASE-T PCS, type 1000BASE-T PMA sublayer, and type 1000BASE-T Medium Dependent Interface (MDI). Together, the PCS and the PMA sublayer comprise a 1000BASE-T Physical layer (PHY). Provided in this document are fully functional, electrical, and mechanical specifications for the type 1000BASE-T PCS, PMA, and MDI. This clause also specifies the baseband medium used with 1000BASE-T.

#### 40.1.1 Objectives

The following are the objectives of 1000BASE-T:

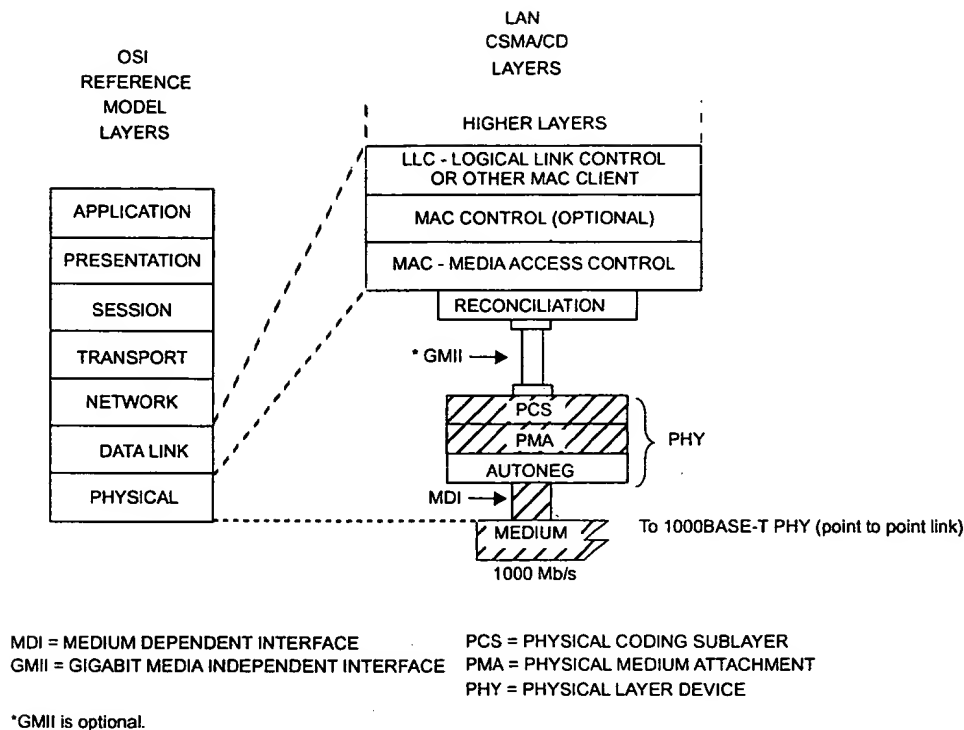
- a) Support the CSMA/CD MAC
- b) Comply with the specifications for the GMII (Clause 35)
- c) Support the 1000Mb/s repeater (Clause 41)
- d) Provide line transmission that supports full and half duplex operation
- e) Meet or exceed FCC Class A/CISPR or better operation
- f) Support operation over 100 meters of Category 5 balanced cabling as defined in 40.7
- g) Bit Error Rate of less than or equal to  $10^{-10}$
- h) Support Auto-Negotiation (Clause 28)

#### 40.1.2 Relationship of 1000BASE-T to other standards

Relations between the 1000BASE-T PHY, the ISO Open Systems Interconnection (OSI) Reference Model, and the IEEE 802.3<sup>®</sup> CSMA/CD LAN Model are shown in Figure 40–1. The PHY sub-layers (shown shaded) in Figure 40–1 connect one Clause 4 Media Access Control (MAC) layer to the medium.

#### 40.1.3 Operation of 1000BASE-T

The 1000BASE-T PHY employs full duplex baseband transmission over four pairs of Category 5 balanced cabling. The aggregate data rate of 1000 Mb/s is achieved by transmission at a data rate of 250 Mb/s over each wire pair, as shown in Figure 40–2. The use of hybrids and cancellers enables full duplex transmission by allowing symbols to be transmitted and received on the same wire pairs at the same time. Baseband signaling with a modulation rate of 125 Mbaud is used on each of the wire pairs. The transmitted symbols are selected from a four-dimensional 5-level symbol constellation. Each four-dimensional symbol can be viewed as a 4-tuple  $(A_n, B_n, C_n, D_n)$  of one-dimensional quinary symbols taken from the set  $\{2, 1, 0, -1, -2\}$ . 1000BASE-T uses a continuous signaling system; in the absence of data, Idle symbols are transmitted. Idle mode is a subset of code-groups in that each symbol is restricted to the set  $\{2, 0, -2\}$  to improve synchronization. Five-level Pulse Amplitude Modulation (PAM5) is employed for transmission over each wire pair. The modulation rate of 125 Mbaud matches the GMII clock rate of 125 MHz and results in a symbol period of 8 ns.

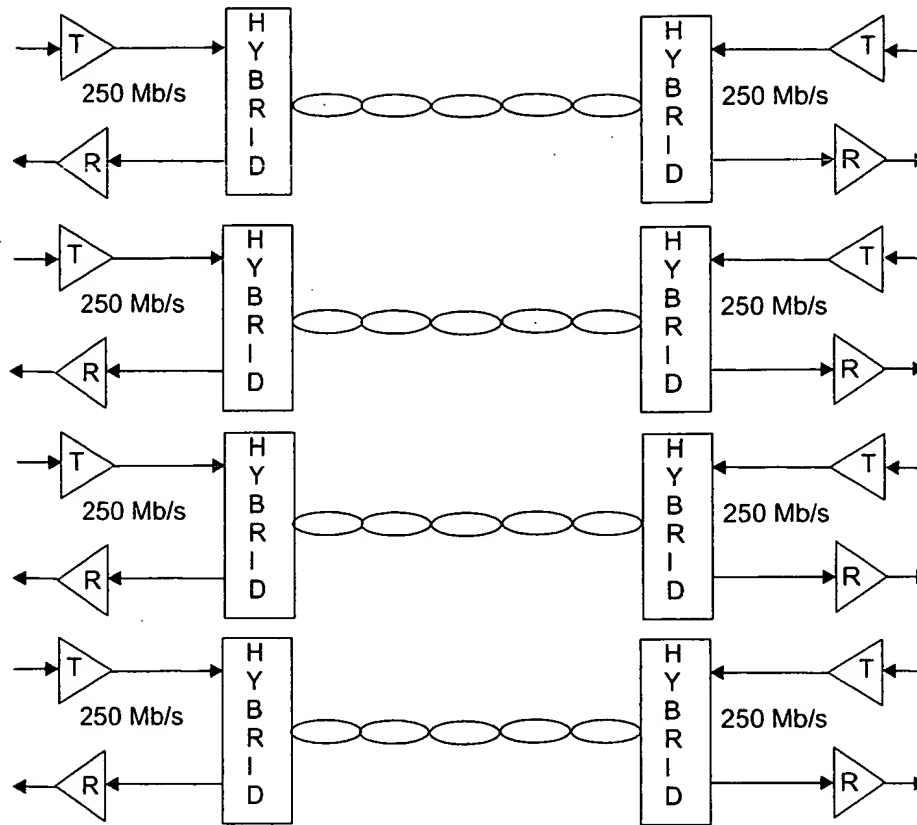


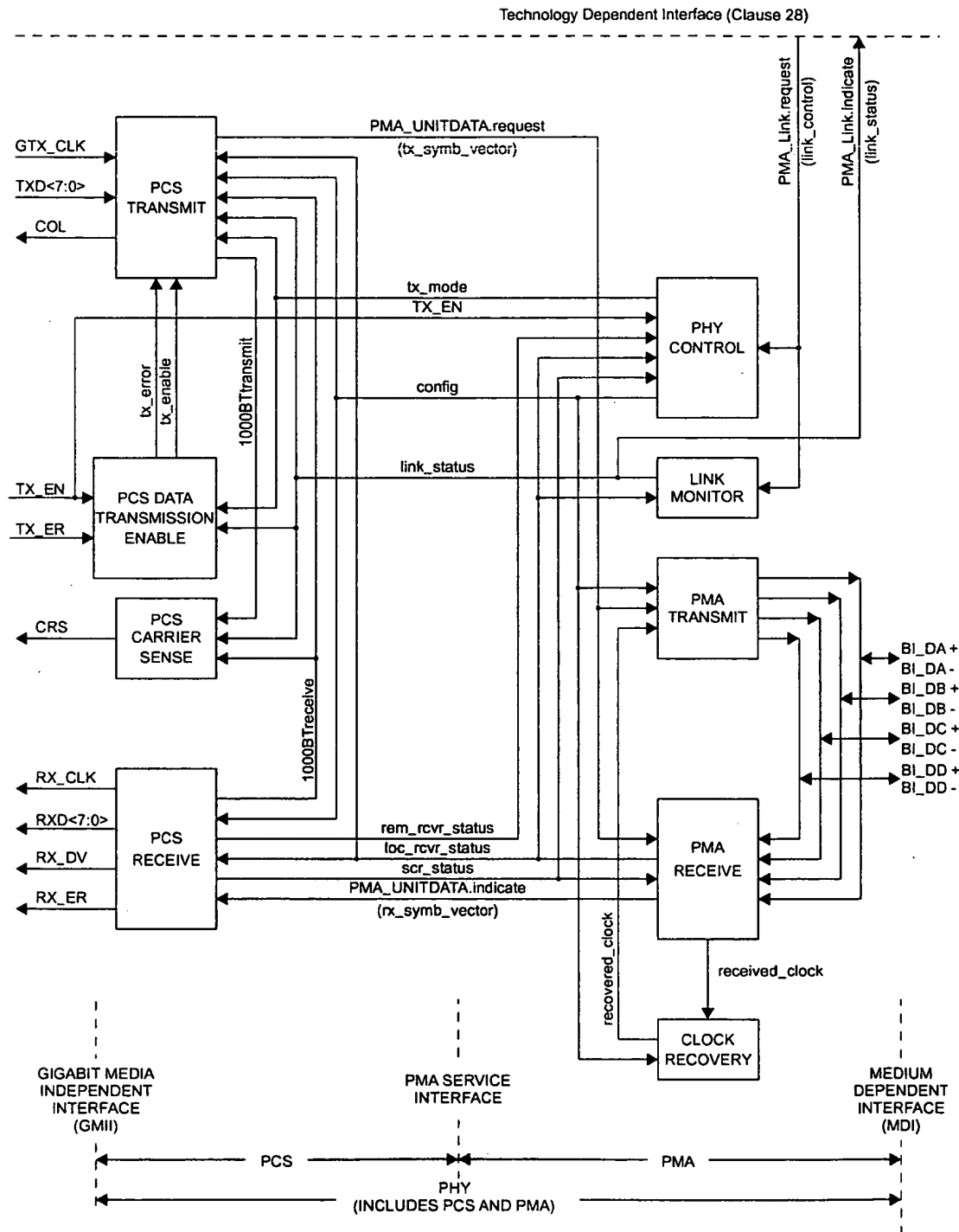
**Figure 40-1 — Type 1000BASE-T PHY relationship to the ISO Open Systems Interconnection (OSI) Reference Model and the IEEE 802.3® CSMA/CD LAN Model**

A 1000BASE-T PHY can be configured either as a MASTER PHY or as a SLAVE PHY. The MASTER-SLAVE relationship between two stations sharing a link segment is established during Auto-Negotiation (see Clause 28, 40.5, and Annex 28C). The MASTER PHY uses a local clock to determine the timing of transmitter operations. The SLAVE PHY recovers the clock from the received signal and uses it to determine the timing of transmitter operations, i.e., it performs loop timing, as illustrated in Figure 40-3. In a multiport to single-port connection, the multiport device is typically set to be MASTER and the single-port device is set to be SLAVE.

The PCS and PMA subclauses of this document are summarized in 40.1.3.1 and 40.1.3.2. Figure 40-3 shows the functional block diagram.



**Figure 40-2—1000BASE-T topology**



NOTE The recovered\_clock arc is shown to indicate delivery of the received clock signal back to PMA TRANSMIT for loop timing.

Figure 40-3—Functional block diagram

#### 40.1.3.1 Physical Coding Sublayer (PCS)

The 1000BASE-T PCS couples a Gigabit Media Independent Interface (GMII), as described in Clause 35, to a Physical Medium Attachment (PMA) sublayer.

The functions performed by the PCS comprise the generation of continuous code-groups to be transmitted over four channels and the processing of code-groups received from the remote PHY. The process of converting data bits to code-groups is called 4D-PAM5, which refers to the four-dimensional 5-level Pulse Amplitude Modulation coding technique used. Through this coding scheme, eight bits are converted to one transmission of four quinary symbols.

During the beginning of a frame's transmission, when TX\_EN is asserted from the GMII, two code-groups representing the Start-of-Stream delimiter are transmitted followed by code-groups representing the octets coming from the GMII. Immediately following the data octets, the GMII sets TX\_EN=FALSE, upon which the end of a frame is transmitted. The end of a frame consists of two convolutional state reset symbol periods and two End-of-Stream delimiter symbol periods. This is followed by an optional series of carrier extend symbol periods and, possibly, the start of a new frame during frame bursting. Otherwise, the end of a frame is followed by a series of symbols encoded in the idle mode. The nature of the encoding that follows the end of a frame is determined by the GMII signals TX\_ER and TXD<7:0> as specified in Clause 35.

Between frames, a special subset of code-groups using only the symbols {2, 0, -2} is transmitted. This is called idle mode. Idle mode encoding takes into account the information of whether the local PHY is operating reliably or not (see 40.4.2.4) and allows this information to be conveyed to the remote station. During normal operation, idle mode is followed by a data mode that begins with a Start-of-Stream delimiter.

Further patterns are used for signaling a transmit error and other control functions during transmission of a data stream.

The PCS Receive processes code-groups provided by the PMA. The PCS Receive detects the beginning and the end of frames of data and, during the reception of data, descrambles and decodes the received code-groups into octets RXD<7:0> that are passed to the GMII. The conversion of code-groups to octets uses an 8B1Q4 data decoding technique. PCS Receive also detects errors in the received sequences and signals them to the GMII. Furthermore, the PCS contains a PCS Carrier Sense function, a PCS Collision Presence function, and a management interface.

The PCS functions and state diagrams are specified in 40.3. The signals provided by the PCS at the GMII conform to the interface requirements of Clause 35. The PCS Service Interfaces to the GMII and the PMA are abstract message-passing interfaces specified in 40.2.

#### 40.1.3.2 Physical Medium Attachment (PMA) sublayer

The PMA couples messages from the PMA service interface onto the balanced cabling physical medium and provides the link management and PHY Control functions. The PMA provides full duplex communications at 125 MBaud over four pairs of balanced cabling up to 100 m in length.

The PMA Transmit function comprises four independent transmitters to generate five-level, pulse-amplitude modulated signals on each of the four pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD, as described in 40.4.3.1.

The PMA Receive function comprises four independent receivers for five-level pulse-amplitude modulated signals on each of the four pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD, as described in 40.4.3.2. This signal encoding technique is referred to as 4D-PAM5. The receivers are responsible for acquiring clock and providing code-groups to the PCS as defined by the PMA\_UNITDATA.indicate message. The PMA also contains functions for Link Monitor.

The PMA PHY Control function generates signals that control the PCS and PMA sublayer operations. PHY Control begins following the completion of Auto-Negotiation and provides the start-up functions required for successful 1000BASE-T operation. It determines whether the PHY operates in a normal state, enabling data transmission over the link segment, or whether the PHY sends special code-groups that represent the idle mode. The latter occurs when either one or both of the PHYs that share a link segment are not operating reliably.

PMA functions and state diagrams are specified in 40.4. PMA electrical specifications are given in 40.6.

#### 40.1.4 Signaling

1000BASE-T signaling is performed by the PCS generating continuous code-group sequences that the PMA transmits over each wire pair. The signaling scheme achieves a number of objectives including

- a) Forward Error Correction (FEC) coded symbol mapping for data.
- b) Algorithmic mapping and inverse mapping from octet data to a quartet of quinary symbols and back.
- c) Uncorrelated symbols in the transmitted symbol stream.
- d) No correlation between symbol streams traveling both directions on any pair combination.
- e) No correlation between symbol streams on pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD.
- f) Idle mode uses a subset of code-groups in that each symbol is restricted to the set {2, 0, -2} to ease synchronization, start-up, and retraining.
- g) Ability to rapidly or immediately determine if a symbol stream represents data or idle or carrier extension.
- h) Robust delimiters for Start-of-Stream delimiter (SSD), End-of-Stream delimiter (ESD), and other control signals.
- i) Ability to signal the status of the local receiver to the remote PHY to indicate that the local receiver is not operating reliably and requires retraining.
- j) Ability to automatically detect and correct for pair swapping and unexpected crossover connections.
- k) Ability to automatically detect and correct for incorrect polarity in the connections.
- l) Ability to automatically correct for differential delay variations across the wire-pairs.

The PHY operates in two basic modes, normal mode or training mode. In normal mode, PCS generates code-groups that represent data, control, or idles for transmission by the PMA. In training mode, the PCS is directed to generate only idle code-groups for transmission by the PMA, which enable the receiver at the other end to train until it is ready to operate in normal mode. (See the PCS reference diagram in 40.2.)

#### 40.1.5 Inter-sublayer interfaces

All implementations of the balanced cabling link are compatible at the MDI. Designers are free to implement circuitry within the PCS and PMA in an application-dependent manner provided that the MDI and GMII (if the GMII is implemented) specifications are met. When the PHY is incorporated within the physical bounds of a single-port device or a multiport device, implementation of the GMII is optional. System operation from the perspective of signals at the MDI and management objects are identical whether the GMII is implemented or not.

#### 40.1.6 Conventions in this clause

The body of this clause contains state diagrams, including definitions of variables, constants, and functions. Should there be a discrepancy between a state diagram and descriptive text, the state diagram prevails.

The notation used in the state diagrams follows the conventions of 21.5.

The values of all components in test circuits shall be accurate to within  $\pm 1\%$  unless otherwise stated.

Default initializations, unless specifically specified, are left to the implementor.

## 40.2 1000BASE-T Service Primitives and Interfaces

1000BASE-T transfers data and control information across the following four service interfaces:

- a) Gigabit Media Independent Interface (GMII)
- b) PMA Service Interface
- c) Medium Dependent Interface (MDI)
- d) Technology-Dependent Interface

The GMII is specified in Clause 35; the Technology-Dependent Interface is specified in Clause 28. The PMA Service Interface is defined in 40.2.2 and the MDI is defined in 40.8.

### 40.2.1 Technology-Dependent Interface

1000BASE-T uses the following service primitives to exchange status indications and control signals across the Technology-Dependent Interface as specified in Clause 28:

PMA\_LINK.request (link\_control)

PMA\_LINK.indicate (link\_status)

#### 40.2.1.1 PMA\_LINK.request

This primitive allows the Auto-Negotiation algorithm to enable and disable operation of the PMA as specified in 28.2.6.2.

##### 40.2.1.1.1 Semantics of the primitive

PMA\_LINK.request (link\_control)

The link\_control parameter can take on one of three values: SCAN\_FOR\_CARRIER, DISABLE, or ENABLE.

SCAN_FOR_CARRIER	Used by the Auto-Negotiation algorithm prior to receiving any fast link pulses. During this mode the PMA reports link_status=FAIL.PHY processes are disabled.
DISABLE	Set by the Auto-Negotiation algorithm in the event fast link pulses are detected. PHY processes are disabled. This allows the Auto-Negotiation algorithm to determine how to configure the link.
ENABLE	Used by Auto-Negotiation to turn control over to the PHY for data processing functions.

##### 40.2.1.1.2 When generated

Auto-Negotiation generates this primitive to indicate a change in link\_control as described in Clause 28.

**40.2.1.1.3 Effect of receipt**

This primitive affects operation of the PMA Link Monitor function as defined in 40.4.2.5.

**40.2.1.2 PMA\_LINK.indicate**

This primitive is generated by the PMA to indicate the status of the underlying medium as specified in 28.2.6.1. This primitive informs the PCS, PMA PHY Control function, and the Auto-Negotiation algorithm about the status of the underlying link.

**40.2.1.2.1 Semantics of the primitive**

PMA\_LINK.indicate (link\_status)

The link\_status parameter can take on one of three values: FAIL, READY, or OK.

FAIL	No valid link established.
READY	The Link Monitor function indicates that a 1000BASE-T link is intact and ready to be established.
OK	The Link Monitor function indicates that a valid 1000BASE-T link is established. Reliable reception of signals transmitted from the remote PHY is possible.

**40.2.1.2.2 When generated**

The PMA generates this primitive continuously to indicate the value of link\_status in compliance with the state diagram given in Figure 40–16.

**40.2.1.2.3 Effect of receipt**

The effect of receipt of this primitive is specified in 40.3.3.1.

**40.2.2 PMA Service Interface**

1000BASE-T uses the following service primitives to exchange symbol vectors, status indications, and control signals across the service interfaces:

PMA\_TXMODE.indicate (tx\_mode)  
 PMA\_CONFIG.indicate (config)  
 PMA\_UNITDATA.request (tx\_symb\_vector)  
 PMA\_UNITDATA.indicate (rx\_symb\_vector)  
 PMA\_SCRSTATUS.request (scr\_status)  
 PMA\_RXSTATUS.indicate (loc\_rcvr\_status)  
 PMA\_REMRXSTATUS.request (rem\_rcvr\_status)

The use of these primitives is illustrated in Figure 40–4.

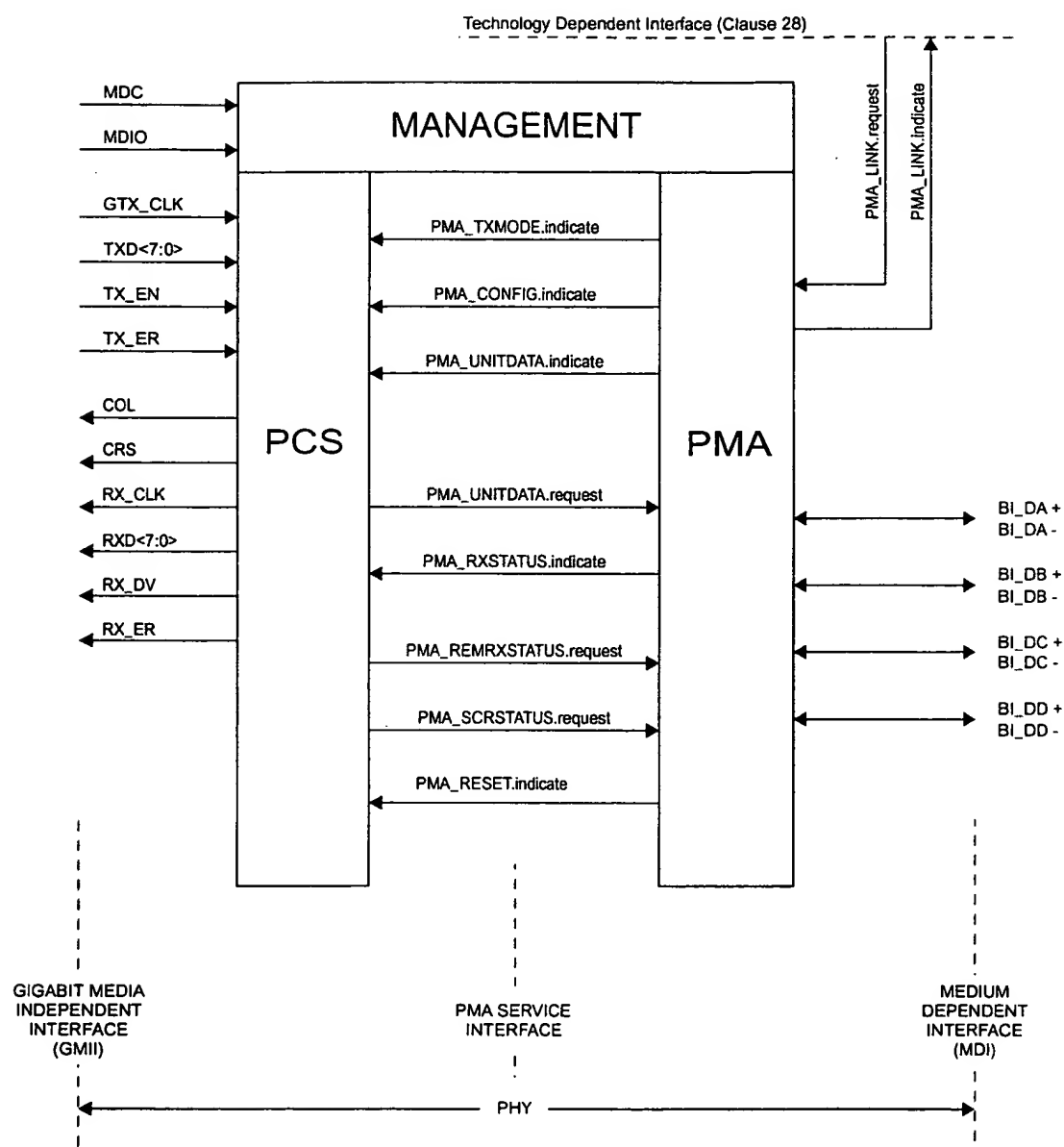


Figure 40-4—1000BASE-T service interfaces

### 40.2.3 PMA\_TXMODE.indicate

The transmitter in a 1000BASE-T link normally sends over the four pairs, code-groups that can represent a GMII data stream, control information, or idles.

#### 40.2.3.1 Semantics of the primitive

PMA\_TXMODE.indicate (tx\_mode)

PMA\_TXMODE.indicate specifies to PCS Transmit via the parameter tx\_mode what sequence of code-groups the PCS should be transmitting. The parameter tx\_mode can take on one of the following three values of the form:

- |        |                                                                                                                                                                            |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| SEND_N | This value is continuously asserted when transmission of sequences of code-groups representing a GMII data stream (data mode), control mode or idle mode is to take place. |
| SEND_I | This value is continuously asserted in case transmission of sequences of code-groups representing the idle mode is to take place.                                          |
| SEND_Z | This value is continuously asserted in case transmission of zeros is required.                                                                                             |

#### 40.2.3.2 When generated

The PMA PHY Control function generates PMA\_TXMODE.indicate messages continuously.

#### 40.2.3.3 Effect of receipt

Upon receipt of this primitive, the PCS performs its Transmit function as described in 40.3.1.3.

### 40.2.4 PMA\_CONFIG.indicate

Each PHY in a 1000BASE-T link is capable of operating as a MASTER PHY and as a SLAVE PHY. MASTER-SLAVE configuration is determined during Auto-Negotiation (40.5). The result of this negotiation is provided to the PMA.

#### 40.2.4.1 Semantics of the primitive

PMA\_CONFIG.indicate (config)

PMA\_CONFIG.indicate specifies to PCS and PMA Transmit via the parameter config whether the PHY must operate as a MASTER PHY or as a SLAVE PHY. The parameter config can take on one of the following two values of the form:

- |        |                                                                                |
|--------|--------------------------------------------------------------------------------|
| MASTER | This value is continuously asserted when the PHY must operate as a MASTER PHY. |
| SLAVE  | This value is continuously asserted when the PHY must operate as a SLAVE PHY.  |

#### 40.2.4.2 When generated

PMA generates PMA\_CONFIG.indicate messages continuously.

#### 40.2.4.3 Effect of receipt

PCS and PMA Clock Recovery perform their functions in MASTER or SLAVE configuration according to the value assumed by the parameter config.

### 40.2.5 PMA\_UNITDATA.request

This primitive defines the transfer of code-groups in the form of the tx\_symb\_vector parameter from the PCS to the PMA. The code-groups are obtained in the PCS Transmit function using the encoding rules defined in 40.3.1.3 to represent GMII data streams, an idle mode, or other sequences.

#### 40.2.5.1 Semantics of the primitive

PMA\_UNITDATA.request (tx\_symb\_vector)



During transmission, the PMA\_UNITDATA.request simultaneously conveys to the PMA via the parameter tx\_symb\_vector the value of the symbols to be sent over each of the four transmit pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD. The tx\_symb\_vector parameter takes on the form:

**SYMB\_4D**      A vector of four quinary symbols, one for each of the four transmit pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD. Each quinary symbol may take on one of the values -2, -1, 0, +1, or +2.

The quinary symbols that are elements of tx\_symb\_vector are called, according to the pair on which each will be transmitted, tx\_symb\_vector[BI\_DA], tx\_symb\_vector[BI\_DB], tx\_symb\_vector[BI\_DC], and tx\_symb\_vector[BI\_DD].

#### 40.2.5.2 When generated

The PCS generates PMA\_UNITDATA.request (SYMB\_4D) synchronously with every transmit clock cycle.

#### 40.2.5.3 Effect of receipt

Upon receipt of this primitive the PMA transmits on the MDI the signals corresponding to the indicated quinary symbols. The parameter tx\_symb\_vector is also used by the PMA Receive function to process the signals received on pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD.

### 40.2.6 PMA\_UNITDATA.indicate

This primitive defines the transfer of code-groups in the form of the rx\_symb\_vector parameter from the PMA to the PCS.

#### 40.2.6.1 Semantics of the primitive

PMA\_UNITDATA.indicate (rx\_symb\_vector)

During reception the PMA\_UNITDATA.indicate simultaneously conveys to the PCS via the parameter rx\_symb\_vector the values of the symbols detected on each of the four receive pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD. The rx\_symb\_vector parameter takes on the form:

**SYMB\_4D**      A vector of four quinary symbols, one for each of the four receive pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD. Each quinary symbol may take on one of the values -2, -1, 0, +1, or +2.

The quinary symbols that are elements of rx\_symb\_vector are called, according to the pair upon which each symbol was received, rx\_symb\_vector[BI\_DA], rx\_symb\_vector[BI\_DB], rx\_symb\_vector[BI\_DC], and rx\_symb\_vector[BI\_DD].

#### 40.2.6.2 When generated

The PMA generates PMA\_UNITDATA.indicate (SYMB\_4D) messages synchronously with signals received at the MDI. The nominal rate of the PMA\_UNITDATA.indicate primitive is 125 MHz, as governed by the recovered clock.

#### 40.2.6.3 Effect of receipt

The effect of receipt of this primitive is unspecified.

#### 40.2.7 PMA\_SCRSTATUS.request

This primitive is generated by PCS Receive to communicate the status of the descrambler for the local PHY. The parameter `scr_status` conveys to the PMA Receive function the information that the descrambler has achieved synchronization.

##### 40.2.7.1 Semantics of the primitive

PMA\_SCRSTATUS.request (`scr_status`)

The `scr_status` parameter can take on one of two values of the form:

OK	The descrambler has achieved synchronization.
NOT_OK	The descrambler is not synchronized.

##### 40.2.7.2 When generated

PCS Receive generates PMA\_SCRSTATUS.request messages continuously.

##### 40.2.7.3 Effect of receipt

The effect of receipt of this primitive is specified in 40.4.2.3, 40.4.2.4, and 40.4.6.1.

#### 40.2.8 PMA\_RXSTATUS.indicate

This primitive is generated by PMA Receive to indicate the status of the receive link at the local PHY. The parameter `loc_rcvr_status` conveys to the PCS Transmit, PCS Receive, PMA PHY Control function, and Link Monitor the information on whether the status of the overall receive link is satisfactory or not. Note that `loc_rcvr_status` is used by the PCS Receive decoding functions. The criterion for setting the parameter `loc_rcvr_status` is left to the implementor. It can be based, for example, on observing the mean-square error at the decision point of the receiver and detecting errors during reception of symbol streams that represent the idle mode.

##### 40.2.8.1 Semantics of the primitive

PMA\_RXSTATUS.indicate (`loc_rcvr_status`)

The `loc_rcvr_status` parameter can take on one of two values of the form:

OK	This value is asserted and remains true during reliable operation of the receive link for the local PHY.
NOT_OK	This value is asserted whenever operation of the link for the local PHY is unreliable.

##### 40.2.8.2 When generated

PMA Receive generates PMA\_RXSTATUS.indicate messages continuously on the basis of signals received at the MDI.

##### 40.2.8.3 Effect of receipt

The effect of receipt of this primitive is specified in Figure 40–15 and in subclauses 40.2 and 40.4.6.2.

#### 40.2.9 PMA\_REMRXSTATUS.request

This primitive is generated by PCS Receive to indicate the status of the receive link at the remote PHY as communicated by the remote PHY via its encoding of its `loc_rcvr_status` parameter. The parameter `rem_rcvr_status` conveys to the PMA PHY Control function the information on whether reliable operation of the remote PHY is detected or not. The criterion for setting the parameter `rem_rcvr_status` is left to the implementor. It can be based, for example, on asserting `rem_rcvr_status` is `NOT_OK` until `loc_rcvr_status` is `OK` and then asserting the detected value of `rem_rcvr_status` after proper PCS receive decoding is achieved.

##### 40.2.9.1 Semantics of the primitive

PMA\_REMRXSTATUS.request (`rem_rcvr_status`)

The `rem_rcvr_status` parameter can take on one of two values of the form:

OK	The receive link for the remote PHY is operating reliably.
NOT_OK	Reliable operation of the receive link for the remote PHY is not detected.

##### 40.2.9.2 When generated

The PCS generates PMA\_REMRXSTATUS.request messages continuously on the basis on signals received at the MDI.

##### 40.2.9.3 Effect of receipt

The effect of receipt of this primitive is specified in Figure 40–15.

#### 40.2.10 PMA\_RESET.indicate

This primitive is used to pass the PMA Reset function to the PCS (`pcs_reset=ON`) when reset is enabled.

The PMA\_RESET.indicate primitive can take on one of two values:

TRUE	Reset is enabled.
FALSE	Reset is not enabled.

##### 40.2.10.1 When generated

The PMA Reset function is executed as described in 40.4.2.1.

##### 40.2.10.2 Effect of receipt

The effect of receipt of this primitive is specified in 40.4.2.1.

### 40.3 Physical Coding Sublayer (PCS)

The PCS comprises one PCS Reset function and four simultaneous and asynchronous operating functions. The PCS operating functions are: PCS Transmit Enable, PCS Transmit, PCS Receive, and PCS Carrier Sense. All operating functions start immediately after the successful completion of the PCS Reset function.

The PCS reference diagram, Figure 40–5, shows how the four operating functions relate to the messages of the PCS-PMA interface. Connections from the management interface (signals MDC and MDIO) to other

layers are pervasive, and are not shown in Figure 40–5. Management is specified in Clause 30. See also Figure 40–7, which defines the structure of frames passed from PCS to PMA.

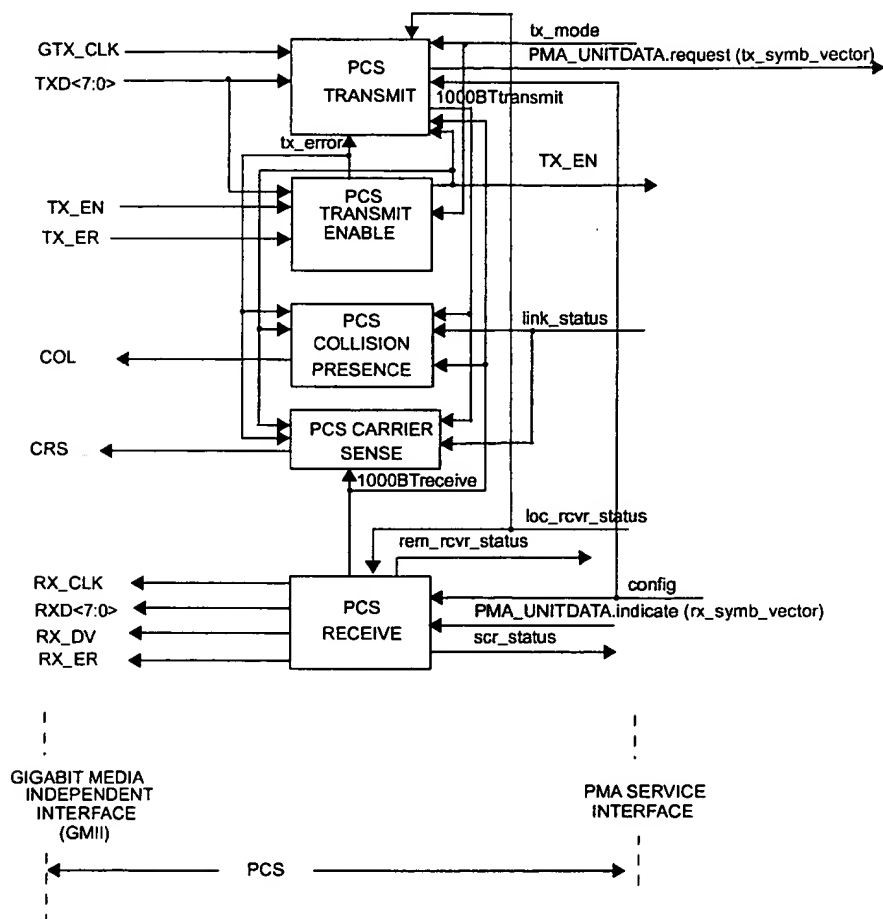


Figure 40–5—PCS reference diagram

### 40.3.1 PCS functions

#### 40.3.1.1 PCS Reset function

PCS Reset initializes all PCS functions. The PCS Reset function shall be executed whenever one of the following conditions occur:

- a) Power on (see 36.2.5.1.3).
- b) The receipt of a request for reset from the management entity.

PCS Reset sets pcs\_reset=ON while any of the above reset conditions hold true. All state diagrams take the open-ended pcs\_reset branch upon execution of PCS Reset. The reference diagrams do not explicitly show the PCS Reset function.

### 40.3.1.2 PCS Data Transmission Enable

The PCS Data Transmission Enabling process generates the signals `tx_enable` and `tx_error`, which PCS Transmit uses for data and carrier extension encoding. The process uses logical operations on `tx_mode`, `TX_ER`, `TX_EN`, and `TXD<7:0>`. The PCS shall implement the Data Transmission Enabling process as depicted in Figure 40–8 including compliance with the associated state variables as specified in 40.3.3.

### 40.3.1.3 PCS Transmit function

The PCS Transmit function shall conform to the PCS Transmit state diagram in Figure 40–9.

The PCS Transmit function generates the GMII signal `COL` based on whether a reception is occurring simultaneously with transmission. The PCS Transmit function is not required to generate the GMII signal `COL` in a 1000BASE-T PHY that does not support half duplex operation.

In each symbol period, PCS Transmit generates a code-group ( $A_n, B_n, C_n, D_n$ ) that is transferred to the PMA via the `PMA_UNITDATA.request` primitive. The PMA transmits symbols  $A_n, B_n, C_n, D_n$  over wire-pairs `BI_DA`, `BI_DB`, `BI_DC`, and `BI_DD` respectively. The integer,  $n$ , is a time index that is introduced to establish a temporal relationship between different symbol periods. A symbol period,  $T$ , is nominally equal to 8 ns. In normal mode of operation, between streams of data indicated by the parameter `tx_enable`, PCS Transmit generates sequences of vectors using the encoding rules defined for the idle mode. Upon assertion of `tx_enable`, PCS Transmit passes a SSD of two consecutive vectors of four quinary symbols to the PMA, replacing the first two preamble octets. Following the SSD, each `TXD<7:0>` octet is encoded using an 4D-PAM5 technique into a vector of four quinary symbols until `tx_enable` is de-asserted. If `TX_ER` is asserted while `tx_enable` is also asserted, then PCS Transmit passes to the PMA vectors indicating a transmit error. Note that if the signal `TX_ER` is asserted while SSD is being sent, the transmission of the error condition is delayed until transmission of SSD has been completed. Following the de-assertion of `tx_enable`, a Convolutional State Reset (CSReset) of two consecutive code-groups, followed by an ESD of two consecutive code-groups, is generated, after which the transmission of idle or control mode is resumed.

If a `PMA_TXMODE.indicate` message has the value `SEND_Z`, PCS Transmit passes a vector of zeros at each symbol period to the PMA via the `PMA_UNITDATA.request` primitive.

If a `PMA_TXMODE.indicate` message has the value `SEND_I`, PCS Transmit generates sequences of code-groups according to the encoding rule in training mode. Special code-groups that use only the values  $\{+2, 0, -2\}$  are transmitted in this case. Training mode encoding also takes into account the value of the parameter `loc_rcvr_status`. By this mechanism, a PHY indicates the status of its own receiver to the link partner during idle transmission.

In the normal mode of operation, the `PMA_TXMODE.indicate` message has the value `SEND_N`, and the PCS Transmit function uses an 8B1Q4 coding technique to generate at each symbol period code-groups that represent data, control or idle based on the code-groups defined in Table 40–1 and Table 40–2. During transmission of data, the `TXD<7:0>` bits are scrambled by the PCS using a side-stream scrambler, then encoded into a code-group of quinary symbols and transferred to the PMA. During data encoding, PCS Transmit utilizes a three-state convolutional encoder.

The transition from idle or carrier extension to data is signalled by inserting a SSD, and the end of transmission of data is signalled by an ESD. Further code-groups are reserved for signaling the assertion of `TX_ER` within a stream of data, carrier extension, CSReset, and other control functions. During idle and carrier extension encoding, special code-groups with symbol values restricted to the set  $\{2, 0, -2\}$  are used. These code-groups are also generated using the transmit side-stream scrambler. However, the encoding rules for the idle, SSD, and carrier extend code-groups are different from the encoding rules for data, CSReset, CSExtend, and ESD code-groups. During idle, SSD, and carrier extension, the PCS Transmit function reverses the sign of the transmitted symbols. This allows, at the receiver, sequences of code-groups that represent data,

CSReset, CSExtend, and ESD to be easily distinguished from sequences of code-groups that represent SSD, carrier extension, and idle.

PCS encoding involves the generation of the four-bit words  $Sx_n[3:0]$ ,  $Sy_n[3:0]$ , and  $Sg_n[3:0]$  from which the quinary symbols ( $A_n$ ,  $B_n$ ,  $C_n$ ,  $D_n$ ) are obtained. The four-bit words  $Sx_n[3:0]$ ,  $Sy_n[3:0]$ , and  $Sg_n[3:0]$  are determined (as explained in 40.3.1.3.2) from sequences of pseudorandom binary symbols derived from the transmit side-stream scrambler.

#### 40.3.1.3.1 Side-stream scrambler polynomials

The PCS Transmit function employs side-stream scrambling. If the parameter config provided to the PCS by the PMA PHY Control function via the PMA\_CONFIG.indicate message assumes the value MASTER, PCS Transmit shall employ

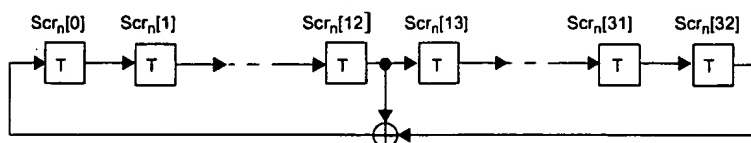
$$g_M(x) = 1 + x^{13} + x^{33}$$

as transmitter side-stream scrambler generator polynomial. If the PMA\_CONFIG.indicate message assumes the value of SLAVE, PCS Transmit shall employ

$$g_S(x) = 1 + x^{20} + x^{33}$$

as transmitter side-stream scrambler generator polynomial. An implementation of master and slave PHY side-stream scramblers by linear-feedback shift registers is shown in Figure 40–6. The bits stored in the shift register delay line at time  $n$  are denoted by  $Scr_n[32:0]$ . At each symbol period, the shift register is advanced by one bit, and one new bit represented by  $Scr_n[0]$  is generated. The transmitter side-stream scrambler is reset upon execution of the PCS Reset function. If PCS Reset is executed, all bits of the 33-bit vector representing the side-stream scrambler state are arbitrarily set. The initialization of the scrambler state is left to the implementor. In no case shall the scrambler state be initialized to all zeros.

Side-stream scrambler employed by the MASTER PHY



Side-stream scrambler employed by the SLAVE PHY

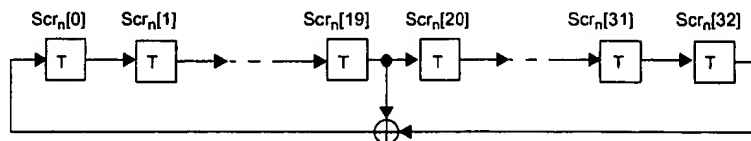


Figure 40–6—A realization of side-stream scramblers by linear feedback shift registers

#### 40.3.1.3.2 Generation of bits $Sx_n[3:0]$ , $Sy_n[3:0]$ , and $Sg_n[3:0]$

PCS Transmit encoding rules are based on the generation, at time  $n$ , of the twelve bits  $Sx_n[3:0]$ ,  $Sy_n[3:0]$ , and  $Sg_n[3:0]$ . The eight bits,  $Sx_n[3:0]$  and  $Sy_n[3:0]$ , are used to generate the scrambler octet  $Sc_n[7:0]$  for decorrelating the GMII data word  $TXD<7:0>$  during data transmission and for generating the idle and training symbols. The four bits,  $Sg_n[3:0]$ , are used to randomize the signs of the quinary symbols ( $A_n$ ,  $B_n$ ,  $C_n$ ,

$D_n$ ) so that each symbol stream has no dc bias. These twelve bits are generated in a systematic fashion using three bits,  $X_n$ ,  $Y_n$ , and  $Scr_n[0]$ , and an auxiliary generating polynomial,  $g(x)$ . The two bits,  $X_n$  and  $Y_n$ , are mutually uncorrelated and also uncorrelated with the bit  $Scr_n[0]$ . For both master and slave PHYs, they are obtained by the same linear combinations of bits stored in the transmit scrambler shift register delay line. These two bits are derived from elements of the same maximum-length shift register sequence of length  $2^{33} - 1$  as  $Scr_n[0]$ , but shifted in time. The associated delays are all large and different so that there is no short-term correlation among the bits  $Scr_n[0]$ ,  $X_n$ , and  $Y_n$ . The bits  $X_n$  and  $Y_n$  are generated as follows:

$$X_n = Scr_n[4] \wedge Scr_n[6]$$

$$Y_n = Scr_n[1] \wedge Scr_n[5]$$

where  $\wedge$  denotes the XOR logic operator. From the three bits  $X_n$ ,  $Y_n$ , and  $Scr_n[0]$ , further mutually uncorrelated bit streams are obtained systematically using the generating polynomial

$$g(x) = x^3 \wedge x^8$$

The four bits  $Sy_n[3:0]$  are generated using the bit  $Scr_n[0]$  and  $g(x)$  as in the following equations:

$$Sy_n[0] = Scr_n[0]$$

$$Sy_n[1] = g(Scr_n[0]) = Scr_n[3] \wedge Scr_n[8]$$

$$Sy_n[2] = g^2(Scr_n[0]) = Scr_n[6] \wedge Scr_n[16]$$

$$Sy_n[3] = g^3(Scr_n[0]) = Scr_n[9] \wedge Scr_n[14] \wedge Scr_n[19] \wedge Scr_n[24]$$

The four bits  $Sx_n[3:0]$  are generated using the bit  $X_n$  and  $g(x)$  as in the following equations:

$$Sx_n[0] = X_n = Scr_n[4] \wedge Scr_n[6]$$

$$Sx_n[1] = g(X_n) = Scr_n[7] \wedge Scr_n[9] \wedge Scr_n[12] \wedge Scr_n[14]$$

$$Sx_n[2] = g^2(X_n) = Scr_n[10] \wedge Scr_n[12] \wedge Scr_n[20] \wedge Scr_n[22]$$

$$Sx_n[3] = g^3(X_n) = Scr_n[13] \wedge Scr_n[15] \wedge Scr_n[18] \wedge Scr_n[20] \wedge \\ Scr_n[23] \wedge Scr_n[25] \wedge Scr_n[28] \wedge Scr_n[30]$$

The four bits  $Sg_n[3:0]$  are generated using the bit  $Y_n$  and  $g(x)$  as in the following equations:

$$Sg_n[0] = Y_n = Scr_n[1] \wedge Scr_n[5]$$

$$Sg_n[1] = g(Y_n) = Scr_n[4] \wedge Scr_n[8] \wedge Scr_n[9] \wedge Scr_n[13]$$

$$Sg_n[2] = g^2(Y_n) = Scr_n[7] \wedge Scr_n[11] \wedge Scr_n[17] \wedge Scr_n[21]$$

$$Sg_n[3] = g^3(Y_n) = Scr_n[10] \wedge Scr_n[14] \wedge Scr_n[15] \wedge Scr_n[19] \wedge \\ Scr_n[20] \wedge Scr_n[24] \wedge Scr_n[25] \wedge Scr_n[29]$$

By construction, the twelve bits  $Sx_n[3:0]$ ,  $Sy_n[3:0]$ , and  $Sg_n[3:0]$  are derived from elements of the same maximum-length shift register sequence of length  $2^{33} - 1$  as  $Scr_n[0]$ , but shifted in time by varying delays. The associated delays are all large and different so that there is no apparent correlation among the bits.

**40.3.1.3.3 Generation of bits  $Sc_n[7:0]$** 

The bits  $Sc_n[7:0]$  are used to scramble the GMII data octet TXD[7:0] and for control, idle, and training mode quartet generation. The definition of these bits is dependent upon the bits  $Sx_n[3:0]$  and  $Sy_n[3:0]$  that are specified in 40.3.1.3.2, the variable  $tx\_mode$  that is obtained through the PMA Service Interface, the variable  $tx\_enable_n$  that is defined in Figure 40–8, and the time index  $n$ .

The four bits  $Sc_n[7:4]$  are defined as

$$Sc_n[7:4] = \begin{cases} Sx_n[3:0] & \text{if } (tx\_enable_{n-2} = 1) \\ [0\ 0\ 0\ 0] & \text{else} \end{cases}$$

The bits  $Sc_n[3:1]$  are defined as

$$Sc_n[3:1] = \begin{cases} [0\ 0\ 0] & \text{if } (tx\_mode = SEND\_Z) \\ Sy_n[3:1] & \text{else if } (n-n_0) = 0 \pmod{2} \\ (Sy_{n-1}[3:1] \wedge [1\ 1\ 1]) & \text{else} \end{cases}$$

where  $n_0$  denotes the time index of the last transmitter side-stream scrambler reset.

The bit  $Sc_n[0]$  is defined as

$$Sc_n[0] = \begin{cases} 0 & \text{if } (tx\_mode = SEND\_Z) \\ Sy_n[0] & \text{else} \end{cases}$$

**40.3.1.3.4 Generation of bits  $Sd_n[8:0]$** 

The PCS Transmit function generates a nine-bit word  $Sd_n[8:0]$  from  $Sc_n$  that represents either a convolutionally encoded stream of data, control, or idle mode code-groups. The convolutional encoder uses a three-bit word  $cs_n[2:0]$ , which is defined as

$$cs_n[1] = \begin{cases} Sd_n[6] \wedge cs_{n-1}[0] & \text{if } (tx\_enable_{n-2} = 1) \\ 0 & \text{else} \end{cases}$$

$$cs_n[2] = \begin{cases} Sd_n[7] \wedge cs_{n-1}[1] & \text{if } (tx\_enable_{n-2} = 1) \\ 0 & \text{else} \end{cases}$$

$$cs_n[0] = cs_{n-1}[2]$$

from which  $Sd_n[8]$  is obtained as

$$Sd_n[8] = cs_n[0]$$



The convolutional encoder bits are non-zero only during the transmission of data. Upon the completion of a data frame, the convolutional encoder bits are reset using the bit  $csreset_n$ . The bit  $csreset_n$  is defined as

$$csreset_n = (tx\_enable_{n-2}) \text{ and } (\text{not } tx\_enable_n)$$

The bits  $Sd_n[7:6]$  are derived from the bits  $Sc_n[7:6]$ , the GMII data bits  $TXD_n[7:6]$ , and from the convolutional encoder bits as

$$Sd_n[7] = \begin{cases} Sc_n[7] \wedge TXD_n[7] & \text{if } (csreset_n = 0 \text{ and } tx\_enable_{n-2} = 1) \\ cs_{n-1}[1] & \text{else if } (csreset_n = 1) \\ Sc_n[7] & \text{else} \end{cases}$$

$$Sd_n[6] = \begin{cases} Sc_n[6] \wedge TXD_n[6] & \text{if } (csreset_n = 0 \text{ and } tx\_enable_{n-2} = 1) \\ cs_{n-1}[0] & \text{else if } (csreset_n = 1) \\ Sc_n[6] & \text{else} \end{cases}$$

The bits  $Sd_n[5:3]$  are derived from the bits  $Sc_n[5:3]$  and the GMII data bits  $TXD_n[5:3]$  as

$$Sd_n[5:3] = \begin{cases} Sc_n[5:3] \wedge TXD_n[5:3] & \text{if } (tx\_enable_{n-2} = 1) \\ Sc_n[5:3] & \text{else} \end{cases}$$

The bit  $Sd_n[2]$  is used to scramble the GMII data bit  $TXD_n[2]$  during data mode and to encode  $loc\_rcvr\_status$  otherwise. It is defined as

$$Sd_n[2] = \begin{cases} Sc_n[2] \wedge TXD_n[2] & \text{if } (tx\_enable_{n-2} = 1) \\ Sc_n[2] \wedge 1 & \text{else if } (loc\_rcvr\_status = \text{OK}) \\ Sc_n[2] & \text{else} \end{cases}$$

The bits  $Sd_n[1:0]$  are used to transmit carrier extension information during  $tx\_mode = \text{SEND\_N}$  and are thus dependent upon the bits  $cext_n$  and  $cext\_err_n$ . These bits are dependent on the variable  $tx\_error_n$ , which is defined in Figure 40–8. These bits are defined as

$$cext_n = \begin{cases} tx\_error_n & \text{if } ((tx\_enable_n = 0) \text{ and } (TXD_n[7:0] = 0x0F)) \\ 0 & \text{else} \end{cases}$$

$$cext\_err_n = \begin{cases} tx\_error_n & \text{if } ((tx\_enable_n = 0) \text{ and } (TXD_n[7:0] \neq 0x0F)) \\ 0 & \text{else} \end{cases}$$

$$Sd_n[1] = \begin{cases} Sc_n[1] \wedge TXD_n[1] & \text{if } (tx\_enable_{n-2} = 1) \\ Sc_n[1] \wedge cext\_err_n & \text{else} \end{cases}$$

$$Sd_n[0] = \begin{cases} Sc_n[0] \wedge TXD_n[0] & \text{if } (tx\_enable_{n-2} = 1) \\ Sc_n[0] \wedge cext_n & \text{else} \end{cases}$$

#### 40.3.1.3.5 Generation of quinary symbols $TA_n, TB_n, TC_n, TD_n$

The nine-bit word  $Sd_n[8:0]$  is mapped to a quartet of quinary symbols ( $TA_n, TB_n, TC_n, TD_n$ ) according to Table 40–1 and Table 40–2 shown as  $Sd_n[6:8] + Sd_n[5:0]$ .

##### *Encoding of error indication:*

If  $tx\_error_n=1$  when the condition  $(tx\_enable_n * tx\_enable_{n-2}) = 1$ , error indication is signaled by means of symbol substitution. In this condition, the values of  $Sd_n[5:0]$  are ignored during mapping and the symbols corresponding to the row denoted as “xmt\_err” in Table 40–1 and Table 40–2 shall be used.

##### *Encoding of Convolutional Encoder Reset:*

If  $tx\_error_n=0$  when the variable  $csreset_n = 1$ , the convolutional encoder reset condition is normal. This condition is indicated by means of symbol substitution, where the values of  $Sd_n[5:0]$  are ignored during mapping and the symbols corresponding to the row denoted as “CSReset” in Table 40–1 and Table 40–2 shall be used.

##### *Encoding of Carrier Extension during Convolutional Encoder Reset:*

If  $tx\_error_n=1$  when the variable  $csreset_n = 1$ , the convolutional encoder reset condition indicates carrier extension. In this condition, the values of  $Sd_n[5:0]$  are ignored during mapping and the symbols corresponding to the row denoted as “CSExtend” in Table 40–1 and Table 40–2 shall be used when  $TXD_n = 0x'0F$ , and the row denoted as “CSExtend\_Err” in Table 40–1 and Table 40–2 shall be used when  $TXD_n \neq 0x'0F$ . The latter condition denotes carrier extension with error. In case carrier extension with error is indicated during the first octet of CSReset, the error condition shall be encoded during the second octet of CSReset, and during the subsequent two octets of the End-of-Stream delimiter as well. Thus, the error condition is assumed to persist during the symbol substitutions at the End-of-Stream.

##### *Encoding of Start-of-Stream delimiter:*

The Start-of-Stream delimiter (SSD) is related to the condition  $SSD_n$ , which is defined as  $(tx\_enable_n) * (!tx\_enable_{n-2}) = 1$ , where “\*” and “!” denote the logic AND and NOT operators, respectively. For the generation of SSD, the first two octets of the preamble in a data stream are mapped to the symbols corresponding to the rows denoted as SSD1 and SSD2 respectively in Table 40–1. The symbols corresponding to the SSD1 row shall be used when the condition  $(tx\_enable_n) * (!tx\_enable_{n-1}) = 1$ . The symbols corresponding to the SSD2 row shall be used when the condition  $(tx\_enable_n) * (!tx\_enable_{n-1}) * (!tx\_enable_{n-2}) = 1$ .

##### *Encoding of End-of-Stream delimiter:*

The definition of an End-of-Stream delimiter (ESD) is related to the condition  $ESD_n$ , which is defined as  $(!tx\_enable_{n-2}) * (tn\_enable_{n-4}) = 1$ . This occurs during the third and fourth symbol periods after transmission of the last octet of a data stream.

If carrier extend error is indicated during ESD, the symbols corresponding to the ESD\_Ext\_Err row shall be used. The two conditions upon which this may occur are

$$(tx\_error_n) * (tx\_error_{n-1}) * (tx\_error_{n-2}) * (TXD_n \neq 0x'0F) = 1, \text{ and}$$

$$(tx\_error_n) * (tx\_error_{n-1}) * (tx\_error_{n-2}) * (tx\_error_{n-3}) * (TXD_n \neq 0x0F) = 1.$$

The symbols corresponding to the ESD1 row in Table 40-1 shall be used when the condition  $(!tx\_enable_{n-2}) * (tx\_enable_{n-3}) = 1$ , in the absence of carrier extend error indication at time  $n$ .

The symbols corresponding to the ESD2\_Ext\_0 row in Table 40-1 shall be used when the condition  $(!tx\_enable_{n-3}) * (tx\_enable_{n-4}) * (!tx\_error_n) * (!tx\_error_{n-1}) = 1$ .

The symbols corresponding to the ESD2\_Ext\_1 row in Table 40-1 shall be used when the condition  $(!tx\_enable_{n-3}) * (tx\_enable_{n-4}) * (!tx\_error_n) * (tx\_error_{n-1}) * (tx\_error_{n-2}) * (tx\_error_{n-3}) = 1$ .

The symbols corresponding to the ESD2\_Ext\_2 row in Table 40-1 shall be used when the condition  $(!tx\_enable_{n-3}) * (tx\_enable_{n-4}) * (tx\_error_n) * (tx\_error_{n-1}) * (tx\_error_{n-2}) * (tx\_error_{n-3}) * (TXD_n = 0x0F) = 1$ , in the absence of carrier extend error indication.

NOTE—The ASCII for Table 40-1 and Table 40-2 is available from <http://www.ieee802.org/3/publication/index.html>.<sup>8</sup>

**Table 40-1—Bit-to-symbol mapping (even subsets)**

		$Sd_n[6:8] = [000]$	$Sd_n[6:8] = [010]$	$Sd_n[6:8] = [100]$	$Sd_n[6:8] = [110]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Normal	000000	0, 0, 0, 0	0, 0, +1, +1	0, +1, +1, 0	0, +1, 0, +1
Normal	000001	-2, 0, 0, 0	-2, 0, +1, +1	-2, +1, +1, 0	-2, +1, 0, +1
Normal	000010	0, -2, 0, 0	0, -2, +1, +1	0, -1, +1, 0	0, -1, 0, +1
Normal	000011	-2, -2, 0, 0	-2, -2, +1, +1	-2, -1, +1, 0	-2, -1, 0, +1
Normal	000100	0, 0, -2, 0	0, 0, -1, +1	0, +1, -1, 0	0, +1, -2, +1
Normal	000101	-2, 0, -2, 0	-2, 0, -1, +1	-2, +1, -1, 0	-2, +1, -2, +1
Normal	000110	0, -2, -2, 0	0, -2, -1, +1	0, -1, -1, 0	0, -1, -2, +1
Normal	000111	-2, -2, -2, 0	-2, -2, -1, +1	-2, -1, -1, 0	-2, -1, -2, +1
Normal	001000	0, 0, 0, -2	0, 0, +1, -1	0, +1, +1, -2	0, +1, 0, -1
Normal	001001	-2, 0, 0, -2	-2, 0, +1, -1	-2, +1, +1, -2	-2, +1, 0, -1
Normal	001010	0, -2, 0, -2	0, -2, +1, -1	0, -1, +1, -2	0, -1, 0, -1
Normal	001011	-2, -2, 0, -2	-2, -2, +1, -1	-2, -1, +1, -2	-2, -1, 0, -1
Normal	001100	0, 0, -2, -2	0, 0, -1, -1	0, +1, -1, -2	0, +1, -2, -1
Normal	001101	-2, 0, -2, -2	-2, 0, -1, -1	-2, +1, -1, -2	-2, +1, -2, -1
Normal	001110	0, -2, -2, -2	0, -2, -1, -1	0, -1, -1, -2	0, -1, -2, -1
Normal	001111	-2, -2, -2, -2	-2, -2, -1, -1	-2, -1, -1, -2	-2, -1, -2, -1
Normal	010000	+1, +1, +1, +1	+1, +1, 0, 0	+1, 0, 0, +1	+1, 0, +1, 0
Normal	010001	-1, +1, +1, +1	-1, +1, 0, 0	-1, 0, 0, +1	-1, 0, +1, 0
Normal	010010	+1, -1, +1, +1	+1, -1, 0, 0	+1, -2, 0, +1	+1, -2, +1, 0

<sup>8</sup>Copyright release for symbol codes: Users of this standard may freely reproduce the symbol codes in this subclause so it can be used for its intended purpose.

Table 40–1—Bit-to-symbol mapping (even subsets) (*continued*)

		$Sd_n[6:8] = [000]$	$Sd_n[6:8] = [010]$	$Sd_n[6:8] = [100]$	$Sd_n[6:8] = [110]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Normal	010011	-1,-1,+1,+1	-1,-1,0,0	-1,-2,0,+1	-1,-2,+1,0
Normal	010100	+1,+1,-1,+1	+1,+1,-2,0	+1,0,-2,+1	+1,0,-1,0
Normal	010101	-1,+1,-1,+1	-1,+1,-2,0	-1,0,-2,+1	-1,0,-1,0
Normal	010110	+1,-1,-1,+1	+1,-1,-2,0	+1,-2,-2,+1	+1,-2,-1,0
Normal	010111	-1,-1,-1,+1	-1,-1,-2,0	-1,-2,-2,+1	-1,-2,-1,0
Normal	011000	+1,+1,+1,-1	+1,+1,0,-2	+1,0,0,-1	+1,0,+1,-2
Normal	011001	-1,+1,+1,-1	-1,+1,0,-2	-1,0,0,-1	-1,0,+1,-2
Normal	011010	+1,-1,+1,-1	+1,-1,0,-2	+1,-2,0,-1	+1,-2,+1,-2
Normal	011011	-1,-1,+1,-1	-1,-1,0,-2	-1,-2,0,-1	-1,-2,+1,-2
Normal	011100	+1,+1,-1,-1	+1,+1,-2,-2	+1,0,-2,-1	+1,0,-1,-2
Normal	011101	-1,+1,-1,-1	-1,+1,-2,-2	-1,0,-2,-1	-1,0,-1,-2
Normal	011110	+1,-1,-1,-1	+1,-1,-2,-2	+1,-2,-2,-1	+1,-2,-1,-2
Normal	011111	-1,-1,-1,-1	-1,-1,-2,-2	-1,-2,-2,-1	-1,-2,-1,-2
Normal	100000	+2,0,0,0	+2,0,+1,+1	+2,+1,+1,0	+2,+1,0,+1
Normal	100001	+2,-2,0,0	+2,-2,+1,+1	+2,-1,+1,0	+2,-1,0,+1
Normal	100010	+2,0,-2,0	+2,0,-1,+1	+2,+1,-1,0	+2,+1,-2,+1
Normal	100011	+2,-2,-2,0	+2,-2,-1,+1	+2,-1,-1,0	+2,-1,-2,+1
Normal	100100	+2,0,0,-2	+2,0,+1,-1	+2,+1,+1,-2	+2,+1,0,-1
Normal	100101	+2,-2,0,-2	+2,-2,+1,-1	+2,-1,+1,-2	+2,-1,0,-1
Normal	100110	+2,0,-2,-2	+2,0,-1,-1	+2,+1,-1,-2	+2,+1,-2,-1
Normal	100111	+2,-2,-2,-2	+2,-2,-1,-1	+2,-1,-1,-2	+2,-1,-2,-1
Normal	101000	0,0,+2,0	+1,+1,+2,0	+1,0,+2,+1	0,+1,+2,+1
Normal	101001	-2,0,+2,0	-1,+1,+2,0	-1,0,+2,+1	-2,+1,+2,+1
Normal	101010	0,-2,+2,0	+1,-1,+2,0	+1,-2,+2,+1	0,-1,+2,+1
Normal	101011	-2,-2,+2,0	-1,-1,+2,0	-1,-2,+2,+1	-2,-1,+2,+1
Normal	101100	0,0,+2,-2	+1,+1,+2,-2	+1,0,+2,-1	0,+1,+2,-1
Normal	101101	-2,0,+2,-2	-1,+1,+2,-2	-1,0,+2,-1	-2,+1,+2,-1
Normal	101110	0,-2,+2,-2	+1,-1,+2,-2	+1,-2,+2,-1	0,-1,+2,-1
Normal	101111	-2,-2,+2,-2	-1,-1,+2,-2	-1,-2,+2,-1	-2,-1,+2,-1
Normal	110000	0,+2,0,0	0,+2,+1,+1	+1,+2,0,+1	+1,+2,+1,0
Normal	110001	-2,+2,0,0	-2,+2,+1,+1	-1,+2,0,+1	-1,+2,+1,0

Table 40-1 — Bit-to-symbol mapping (even subsets) (continued)

		$Sd_n[6:8] = [000]$	$Sd_n[6:8] = [010]$	$Sd_n[6:8] = [100]$	$Sd_n[6:8] = [110]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Normal	110010	0,+2,-2,0	0,+2,-1,+1	+1,+2,-2,+1	+1,+2,-1,0
Normal	110011	-2,+2,-2,0	-2,+2,-1,+1	-1,+2,-2,+1	-1,+2,-1,0
Normal	110100	0,+2,0,-2	0,+2,+1,-1	+1,+2,0,-1	+1,+2,+1,-2
Normal	110101	-2,+2,0,-2	-2,+2,+1,-1	-1,+2,0,-1	-1,+2,+1,-2
Normal	110110	0,+2,-2,-2	0,+2,-1,-1	+1,+2,-2,-1	+1,+2,-1,-2
Normal	110111	-2,+2,-2,-2	-2,+2,-1,-1	-1,+2,-2,-1	-1,+2,-1,-2
Normal	111000	0,0,0,+2	+1,+1,0,+2	0,+1,+1,+2	+1,0,+1,+2
Normal	111001	-2,0,0,+2	-1,+1,0,+2	-2,+1,+1,+2	-1,0,+1,+2
Normal	111010	0,-2,0,+2	+1,-1,0,+2	0,-1,+1,+2	+1,-2,+1,+2
Normal	111011	-2,-2,0,+2	-1,-1,0,+2	-2,-1,+1,+2	-1,-2,+1,+2
Normal	111100	0,0,-2,+2	+1,+1,-2,+2	0,+1,-1,+2	+1,0,-1,+2
Normal	111101	-2,0,-2,+2	-1,+1,-2,+2	-2,+1,-1,+2	-1,0,-1,+2
Normal	111110	0,-2,-2,+2	+1,-1,-2,+2	0,-1,-1,+2	+1,-2,-1,+2
Normal	111111	-2,-2,-2,+2	-1,-1,-2,+2	-2,-1,-1,+2	-1,-2,-1,+2
xmt_err	XXXXXX	0,+2,+2,0	+1,+1,+2,+2	+2,+1,+1,+2	+2,+1,+2,+1
CSExtend_Err	XXXXXX	-2,+2,+2,-2	-1,-1,+2,+2	+2,-1,-1,+2	+2,-1,+2,-1
CSExtend	XXXXXX	+2,0,0,+2	+2,+2,+1,+1	+1,+2,+2,+1	+1,+2,+1,+2
CSReset	XXXXXX	+2,-2,-2,+2	+2,+2,-1,-1	-1,+2,+2,-1	-1,+2,-1,+2
SSD1	XXXXXX	+2,+2,+2,+2	—	—	—
SSD2	XXXXXX	+2,+2,+2,-2	—	—	—
ESD1	XXXXXX	+2,+2,+2,+2	—	—	—
ESD2_Ext_0	XXXXXX	+2,+2,+2,-2	—	—	—
ESD2_Ext_1	XXXXXX	+2,+2,-2,+2	—	—	—
ESD2_Ext_2	XXXXXX	+2,-2,+2,+2	—	—	—
ESD_Ext_Err	XXXXXX	-2,+2,+2,+2	—	—	—
Idle/Carrier Extension	000000	0,0,0,0	—	—	—
Idle/Carrier Extension	000001	-2,0,0,0	—	—	—
Idle/Carrier Extension	000010	0,-2,0,0	—	—	—

**Table 40–1—Bit-to-symbol mapping (even subsets) (continued)**

		$Sd_n[6:8] = [000]$	$Sd_n[6:8] = [010]$	$Sd_n[6:8] = [100]$	$Sd_n[6:8] = [110]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Idle/Carrier Extension	000011	-2,-2,0,0	—	—	—
Idle/Carrier Extension	000100	0,0,-2,0	—	—	—
Idle/Carrier Extension	000101	-2,0,-2,0	—	—	—
Idle/Carrier Extension	000110	0,-2,-2,0	—	—	—
Idle/Carrier Extension	000111	-2,-2,-2,0	—	—	—
Idle/Carrier Extension	001000	0,0,0,-2	—	—	—
Idle/Carrier Extension	001001	-2,0,0,-2	—	—	—
Idle/Carrier Extension	001010	0,-2,0,-2	—	—	—
Idle/Carrier Extension	001011	-2,-2,0,-2	—	—	—
Idle/Carrier Extension	001100	0,0,-2,-2	—	—	—
Idle/Carrier Extension	001101	-2,0,-2,-2	—	—	—
Idle/Carrier Extension	001110	0,-2,-2,-2	—	—	—
Idle/Carrier Extension	001111	-2,-2,-2,-2	—	—	—

**Table 40–2—Bit-to-symbol mapping (odd subsets)**

		$Sd_n[6:8] = [001]$	$Sd_n[6:8] = [011]$	$Sd_n[6:8] = [101]$	$Sd_n[6:8] = [111]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Normal	000000	0,0,0,+1	0,0,+1,0	0,+1,+1,+1	0,+1,0,0
Normal	000001	-2,0,0,+1	-2,0,+1,0	-2,+1,+1,+1	-2,+1,0,0
Normal	000010	0,-2,0,+1	0,-2,+1,0	0,-1,+1,+1	0,-1,0,0
Normal	000011	-2,-2,0,+1	-2,-2,+1,0	-2,-1,+1,+1	-2,-1,0,0
Normal	000100	0,0,-2,+1	0,0,-1,0	0,+1,-1,+1	0,+1,-2,0

Table 40–2—Bit-to-symbol mapping (odd subsets) (continued)

		$Sd_n[6:8] = [001]$	$Sd_n[6:8] = [011]$	$Sd_n[6:8] = [101]$	$Sd_n[6:8] = [111]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Normal	000101	-2, 0, -2, +1	-2, 0, -1, 0	-2, +1, -1, +1	-2, +1, -2, 0
Normal	000110	0, -2, -2, +1	0, -2, -1, 0	0, -1, -1, +1	0, -1, -2, 0
Normal	000111	-2, -2, -2, +1	-2, -2, -1, 0	-2, -1, -1, +1	-2, -1, -2, 0
Normal	001000	0, 0, 0, -1	0, 0, +1, -2	0, +1, +1, -1	0, +1, 0, -2
Normal	001001	-2, 0, 0, -1	-2, 0, +1, -2	-2, +1, +1, -1	-2, +1, 0, -2
Normal	001010	0, -2, 0, -1	0, -2, +1, -2	0, -1, +1, -1	0, -1, 0, -2
Normal	001011	-2, -2, 0, -1	-2, -2, +1, -2	-2, -1, +1, -1	-2, -1, 0, -2
Normal	001100	0, 0, -2, -1	0, 0, -1, -2	0, +1, -1, -1	0, +1, -2, -2
Normal	001101	-2, 0, -2, -1	-2, 0, -1, -2	-2, +1, -1, -1	-2, +1, -2, -2
Normal	001110	0, -2, -2, -1	0, -2, -1, -2	0, -1, -1, -1	0, -1, -2, -2
Normal	001111	-2, -2, -2, -1	-2, -2, -1, -2	-2, -1, -1, -1	-2, -1, -2, -2
Normal	010000	+1, +1, +1, 0	+1, +1, 0, +1	+1, 0, 0, 0	+1, 0, +1, +1
Normal	010001	-1, +1, +1, 0	-1, +1, 0, +1	-1, 0, 0, 0	-1, 0, +1, +1
Normal	010010	+1, -1, +1, 0	+1, -1, 0, +1	+1, -2, 0, 0	+1, -2, +1, +1
Normal	010011	-1, -1, +1, 0	-1, -1, 0, +1	-1, -2, 0, 0	-1, -2, +1, +1
Normal	010100	+1, +1, -1, 0	+1, +1, -2, +1	+1, 0, -2, 0	+1, 0, -1, +1
Normal	010101	-1, +1, -1, 0	-1, +1, -2, +1	-1, 0, -2, 0	-1, 0, -1, +1
Normal	010110	+1, -1, -1, 0	+1, -1, -2, +1	+1, -2, -2, 0	+1, -2, -1, +1
Normal	010111	-1, -1, -1, 0	-1, -1, -2, +1	-1, -2, -2, 0	-1, -2, -1, +1
Normal	011000	+1, +1, +1, -2	+1, +1, 0, -1	+1, 0, 0, -2	+1, 0, +1, -1
Normal	011001	-1, +1, +1, -2	-1, +1, 0, -1	-1, 0, 0, -2	-1, 0, +1, -1
Normal	011010	+1, -1, +1, -2	+1, -1, 0, -1	+1, -2, 0, -2	+1, -2, +1, -1
Normal	011011	-1, -1, +1, -2	-1, -1, 0, -1	-1, -2, 0, -2	-1, -2, +1, -1
Normal	011100	+1, +1, -1, -2	+1, +1, -2, -1	+1, 0, -2, -2	+1, 0, -1, -1
Normal	011101	-1, +1, -1, -2	-1, +1, -2, -1	-1, 0, -2, -2	-1, 0, -1, -1
Normal	011110	+1, -1, -1, -2	+1, -1, -2, -1	+1, -2, -2, -2	+1, -2, -1, -1
Normal	011111	-1, -1, -1, -2	-1, -1, -2, -1	-1, -2, -2, -2	-1, -2, -1, -1
Normal	100000	+2, 0, 0, +1	+2, 0, +1, 0	+2, +1, +1, +1	+2, +1, 0, 0
Normal	100001	+2, -2, 0, +1	+2, -2, +1, 0	+2, -1, +1, +1	+2, -1, 0, 0
Normal	100010	+2, 0, -2, +1	+2, 0, -1, 0	+2, +1, -1, +1	+2, +1, -2, 0

Table 40–2—Bit-to-symbol mapping (odd subsets) (*continued*)

		$Sd_n[6:8] = [001]$	$Sd_n[6:8] = [011]$	$Sd_n[6:8] = [101]$	$Sd_n[6:8] = [111]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
Normal	100011	+2,-2,-2,+1	+2,-2,-1,0	+2,-1,-1,+1	+2,-1,-2,0
Normal	100100	+2,0,0,-1	+2,0,+1,-2	+2,+1,+1,-1	+2,+1,0,-2
Normal	100101	+2,-2,0,-1	+2,-2,+1,-2	+2,-1,+1,-1	+2,-1,0,-2
Normal	100110	+2,0,-2,-1	+2,0,-1,-2	+2,+1,-1,-1	+2,+1,-2,-2
Normal	100111	+2,-2,-2,-1	+2,-2,-1,-2	+2,-1,-1,-1	+2,-1,-2,-2
Normal	101000	0,0,+2,+1	+1,+1,+2,+1	+1,0,+2,0	0,+1,+2,0
Normal	101001	-2,0,+2,+1	-1,+1,+2,+1	-1,0,+2,0	-2,+1,+2,0
Normal	101010	0,-2,+2,+1	+1,-1,+2,+1	+1,-2,+2,0	0,-1,+2,0
Normal	101011	-2,-2,+2,+1	-1,-1,+2,+1	-1,-2,+2,0	-2,-1,+2,0
Normal	101100	0,0,+2,-1	+1,+1,+2,-1	+1,0,+2,-2	0,+1,+2,-2
Normal	101101	-2,0,+2,-1	-1,+1,+2,-1	-1,0,+2,-2	-2,+1,+2,-2
Normal	101110	0,-2,+2,-1	+1,-1,+2,-1	+1,-2,+2,-2	0,-1,+2,-2
Normal	101111	-2,-2,+2,-1	-1,-1,+2,-1	-1,-2,+2,-2	-2,-1,+2,-2
Normal	110000	0,+2,0,+1	0,+2,+1,0	+1,+2,0,0	+1,+2,+1,+1
Normal	110001	-2,+2,0,+1	-2,+2,+1,0	-1,+2,0,0	-1,+2,+1,+1
Normal	110010	0,+2,-2,+1	0,+2,-1,0	+1,+2,-2,0	+1,+2,-1,+1
Normal	110011	-2,+2,-2,+1	-2,+2,-1,0	-1,+2,-2,0	-1,+2,-1,+1
Normal	110100	0,+2,0,-1	0,+2,+1,-2	+1,+2,0,-2	+1,+2,+1,-1
Normal	110101	-2,+2,0,-1	-2,+2,+1,-2	-1,+2,0,-2	-1,+2,+1,-1
Normal	110110	0,+2,-2,-1	0,+2,-1,-2	+1,+2,-2,-2	+1,+2,-1,-1
Normal	110111	-2,+2,-2,-1	-2,+2,-1,-2	-1,+2,-2,-2	-1,+2,-1,-1
Normal	111000	+1,+1,+1,+2	0,0,+1,+2	+1,0,0,+2	0,+1,0,+2
Normal	111001	-1,+1,+1,+2	-2,0,+1,+2	-1,0,0,+2	-2,+1,0,+2
Normal	111010	+1,-1,+1,+2	0,-2,+1,+2	+1,-2,0,+2	0,-1,0,+2
Normal	111011	-1,-1,+1,+2	-2,-2,+1,+2	-1,-2,0,+2	-2,-1,0,+2
Normal	111100	+1,+1,-1,+2	0,0,-1,+2	+1,0,-2,+2	0,+1,-2,+2
Normal	111101	-1,+1,-1,+2	-2,0,-1,+2	-1,0,-2,+2	-2,+1,-2,+2
Normal	111110	+1,-1,-1,+2	0,-2,-1,+2	+1,-2,-2,+2	0,-1,-2,+2
Normal	111111	-1,-1,-1,+2	-2,-2,-1,+2	-1,-2,-2,+2	-2,-1,-2,+2
xmt_err	XXXXXX	+2,+2,0,+1	0,+2,+1,+2	+1,+2,+2,0	+2,+1,+2,0



**Table 40-2—Bit-to-symbol mapping (odd subsets) (continued)**

		$Sd_n[6:8] = [001]$	$Sd_n[6:8] = [011]$	$Sd_n[6:8] = [101]$	$Sd_n[6:8] = [111]$
Condition	$Sd_n[5:0]$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$	$TA_n, TB_n, TC_n, TD_n$
CSExtend_Err	XXXXXX	+2,+2,-2,-1	-2,+2,-1,+2	-1,+2,+2,-2	+2,-1,+2,-2
CSExtend	XXXXXX	+2,0,+2,+1	+2,0,+1,+2	+1,0,+2,+2	+2,+1,0,+2
CSReset	XXXXXX	+2,-2,+2,-1	+2,-2,-1,+2	-1,-2,+2,+2	+2,-1,-2,+2

**40.3.1.3.6 Generation of  $A_n, B_n, C_n, D_n$** 

The four bits  $Sg_n[3:0]$  are used to randomize the signs of the quinary symbols ( $A_n, B_n, C_n, D_n$ ) so that each symbol stream has no dc bias. The bits are used to generate binary symbols ( $SnA_n, SnB_n, SnC_n, SnD_n$ ) that, when multiplied by the quinary symbols ( $TA_n, TB_n, TC_n, TD_n$ ), result in ( $A_n, B_n, C_n, D_n$ ).

PCS Transmit ensures a distinction between code-groups transmitted during idle mode plus SSD and those transmitted during other symbol periods. This distinction is accomplished by reversing the mapping of the sign bits when the condition  $(tx\_enable_{n-2} + tx\_enable_{n-4}) = 1$ . This sign reversal is controlled by the variable  $Srev_n$  defined as

$$Srev_n = tx\_enable_{n-2} + tx\_enable_{n-4}$$

The binary symbols  $SnA_n, SnB_n, SnC_n$ , and  $SnD_n$  are defined using  $Sg_n[3:0]$  as

$$SnA_n = \begin{cases} +1 & \text{if } [(Sg_n[0] \wedge Srev_n) = 0] \\ -1 & \text{else} \end{cases}$$

$$SnB_n = \begin{cases} +1 & \text{if } [(Sg_n[1] \wedge Srev_n) = 0] \\ -1 & \text{else} \end{cases}$$

$$SnC_n = \begin{cases} +1 & \text{if } [(Sg_n[2] \wedge Srev_n) = 0] \\ -1 & \text{else} \end{cases}$$

$$SnD_n = \begin{cases} +1 & \text{if } [(Sg_n[3] \wedge Srev_n) = 0] \\ -1 & \text{else} \end{cases}$$

The quinary symbols ( $A_n, B_n, C_n, D_n$ ) are generated as the product of ( $SnA_n, SnB_n, SnC_n, SnD_n$ ) and ( $TA_n, TB_n, TC_n, TD_n$ ) respectively.

$$A_n = TA_n \times SnA_n$$

$$B_n = TB_n \times SnB_n$$

$$C_n = TC_n \times SnC_n$$

$$D_n = TD_n \times SnD_n$$

#### 40.3.1.4 PCS Receive function

The PCS Receive function shall conform to the PCS Receive state diagram in Figure 40–10a including compliance with the associated state variables as specified in 40.3.3.

The PCS Receive function accepts received code-groups provided by the PMA Receive function via the parameter `rx_symb_vector`. To achieve correct operation, PCS Receive uses the knowledge of the encoding rules that are employed in the idle mode. PCS Receive generates the sequence of vectors of four quinary symbols ( $RA_n, RB_n, RC_n, RD_n$ ) and indicates the reliable acquisition of the descrambler state by setting the parameter `scr_status` to OK. The sequence ( $RA_n, RB_n, RC_n, RD_n$ ) is processed to generate the signals  $RXD<7:0>$ ,  $RX\_DV$ , and  $RX\_ER$ , which are presented to the GMII. PCS Receive detects the transmission of a stream of data from the remote station and conveys this information to the PCS Carrier Sense and PCS Transmit functions via the parameter `1000BTreceive`.

##### 40.3.1.4.1 Decoding of code-groups

When the PMA indicates that correct receiver operation has been achieved by setting the `loc_rcvr_status` parameter to the value OK, the PCS Receive continuously checks that the received sequence satisfies the encoding rule used in idle mode. When a violation is detected, PCS Receive assigns the value TRUE to the parameter `1000BTreceive` and, by examining the last two received vectors ( $RA_{n-1}, RB_{n-1}, RC_{n-1}, RD_{n-1}$ ) and ( $RA_n, RB_n, RC_n, RD_n$ ), determines whether the violation is due to reception of SSD or to a receiver error.

Upon detection of SSD, PCS Receive also assigns the value TRUE to the parameter `1000BTreceive` that is provided to the PCS Carrier Sense and Collision Presence functions. During the two symbol periods corresponding to SSD, PCS Receive replaces SSD by preamble bits. Upon the detection of SSD, the signal  $RX\_DV$  is asserted and each received vector is decoded into a data octet  $RXD<7:0>$  until ESD is detected.

Upon detection of a receiver error, the signal  $RX\_ER$  is asserted and the parameter `rxerror_status` assumes the value ERROR. De-assertion of  $RX\_ER$  and transition to the IDLE state (`rxerror_status=NO_ERROR`) takes place upon detection of four consecutive vectors satisfying the encoding rule used in idle mode.

During reception of a stream of data, PCS Receive checks that the symbols  $RA_n, RB_n, RC_n, RD_n$  follow the encoding rule defined in 40.3.1.3.5 for ESD whenever they assume values  $\pm 2$ . PCS Receive processes two consecutive vectors at each time  $n$  to detect ESD. Upon detection of ESD, PCS Receive de-asserts the signal  $RX\_DV$  on the GMII. If the last symbol period of ESD indicates that a carrier extension is present, PCS Receive will assert the  $RX\_ER$  signal on the GMII. If no extension is indicated in the ESD2 quartet, PCS Receive assigns the value FALSE to the parameter `receiving`. If an extension is present, the transition to the IDLE state occurs after detection of a valid idle symbol period and the parameter `receiving` remains TRUE until `check_idle` is TRUE. If a violation of the encoding rules is detected, PCS Receive asserts the signal  $RX\_ER$  for at least one symbol period.

A premature stream termination is caused by the detection of invalid symbols during the reception of a data stream. Then, PCS Receive waits for the reception of four consecutive vectors satisfying the encoding rule used in idle mode prior to de-asserting the error indication. Note that  $RX\_DV$  remains asserted during the symbol periods corresponding to the first three idle vectors, while  $RX\_ER=TRUE$  is signaled on the GMII. The signal  $RX\_ER$  is also asserted in the LINK FAILED state, which ensures that  $RX\_ER$  remains asserted for at least one symbol period.

#### 40.3.1.4.2 Receiver descrambler polynomials

The PHY shall descramble the data stream and return the proper sequence of code-groups to the decoding process for generation of RXD<7:0> to the GMII. For side-stream descrambling, the MASTER PHY shall employ the receiver descrambler generator polynomial  $g'_M(x) = 1 + x^{20} + x^{33}$  and the SLAVE PHY shall employ the receiver descrambler generator polynomial  $g'_S(x) = 1 + x^{13} + x^{33}$ .

#### 40.3.1.5 PCS Carrier Sense function

The PCS Carrier Sense function generates the GMII signal CRS, which the MAC uses for deferral in half duplex mode. The PCS shall conform to the Carrier Sense state diagram as depicted in Figure 40-11 including compliance with the associated state variables as specified in 40.3.3. The PCS Carrier Sense function is not required in a 1000BASE-T PHY that does not support half duplex operation.

#### 40.3.2 Stream structure

The tx\_symb\_vector and rx-symb\_vector structure is shown in Figure 40-7.

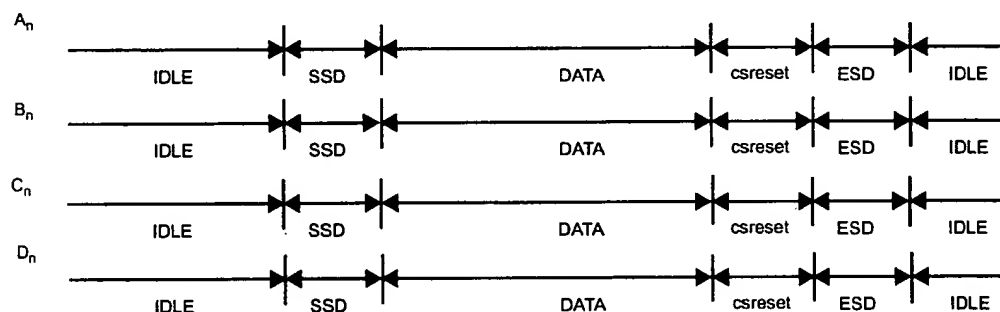


Figure 40-7—The tx\_symb\_vector and rx-symb\_vector structure

#### 40.3.3 State variables

##### 40.3.3.1 Variables

###### CEXT

A vector of four quinary symbols corresponding to the code-group generated in idle mode to denote carrier extension, as specified in 40.3.1.3.

###### CEXT\_Err

A vector of four quinary symbols corresponding to the code-group generated in idle mode to denote carrier extension with error indication, as specified in 40.3.1.3.

###### COL

The COL signal of the GMII as specified in 35.2.2.10.

###### config

The config parameter set by PMA and passed to the PCS via the PMA\_CONFIG.indicate primitive.  
Values: MASTER, SLAVE.

**CRS**

The CRS signal of the GMII as specified in 35.2.2.9.

**CSExtend**

A vector of four quinary symbols corresponding to the code-group indicating convolutional encoder reset condition during carrier extension, as specified in 40.3.1.3.

**CSExtend\_Err**

A vector of four quinary symbols corresponding to the code-group indicating convolutional encoder reset condition during carrier extension with error indication, as specified in 40.3.1.3.

**CSReset**

A vector of four quinary symbols corresponding to the code-group indicating convolutional encoder reset condition in the absence of carrier extension, as specified in 40.3.1.3.

**DATA**

A vector of four quinary symbols corresponding to the code-group indicating valid data, as specified in 40.3.1.3.

**ESD1**

A vector of four quinary symbols corresponding to the first code-group of End-of-Stream delimiter, as specified in 40.3.1.3.

**ESD2\_Ext\_0**

A vector of four quinary symbols corresponding to the second code-group of End-of-Stream delimiter in the absence of carrier extension over the two ESD symbol periods, as specified in 40.3.1.3.

**ESD2\_Ext\_1**

A vector of four quinary symbols corresponding to the second code-group of End-of-Stream delimiter when carrier extension is indicated during the first symbol period of the End-of-Stream delimiter, but not during the second symbol period, as specified in 40.3.1.3.

**ESD2\_Ext\_2**

A vector of four quinary symbols corresponding to the second code-group of End-of-Stream delimiter when carrier extension is indicated during the two symbol periods of the End-of-Stream delimiter, as specified in 40.3.1.3.

**ESD\_Ext\_Err**

A vector of four quinary symbols corresponding to either the first or second code-group of End-of-Stream delimiter when carrier extension with error is indicated during the End-of-Stream delimiter, as specified in 40.3.1.3.

**IDLE**

A sequence of vectors of four quinary symbols representing the special code-group generated in idle mode in the absence of carrier extension or carrier extension with error indication, as specified in 40.3.1.3.

**link\_status**

The link\_status parameter set by PMA Link Monitor and passed to the PCS via the PMA\_LINK.indicate primitive.

Values: OK or FAIL

**loc\_rcvr\_status**

The loc\_rcvr\_status parameter set by the PMA Receive function and passed to the PCS via the PMA\_RXSTATUS.indicate primitive.

Values: OK or NOT\_OK

**pcs\_reset**

The pcs\_reset parameter set by the PCS Reset function.

Values: ON or OFF

**(RA<sub>n</sub>, RB<sub>n</sub>, RC<sub>n</sub>, RD<sub>n</sub>)**

The vector of the four correctly aligned most recently received quinary symbols generated by PCS Receive at time n.

**1000BTreceive**

The receiving parameter generated by the PCS Receive function.

Values: TRUE or FALSE

**rem\_rcvr\_status**

The rem\_rcvr\_status parameter generated by PCS Receive.

Values: OK or NOT\_OK

**repeater\_mode**

See 36.2.5.1.3

**Rx<sub>n</sub>**

Alias for rx\_symb\_vector (a vector RA<sub>n</sub>, RB<sub>n</sub>, RC<sub>n</sub>, RD<sub>n</sub>) at time n.

**rxerror\_status**

The rxerror\_status parameter set by the PCS Receive function.

Values: ERROR or NO\_ERROR

**RX\_DV**

The RX\_DV signal of the GMII as specified in 35.2.2.6.

**RX\_ER**

The RX\_ER signal of the GMII as specified in 35.2.2.8.

**rx\_symb\_vector**

A vector of four quinary symbols received by the PMA and passed to the PCS via the PMA\_UNITDATA.indicate primitive.

Value: SYMB\_4D

**RXD[7:0]**

The RXD<7:0> signal of the GMII as specified in 35.2.2.7.

**SSD1**

A vector of four quinary symbols corresponding to the first code-group of the Start-of-Stream delimiter, as specified in 40.3.1.3.5.

**SSD2**

A vector of four quinary symbols corresponding to the second code-group of the Start-of-Stream delimiter, as specified in 40.3.1.3.5.

**1000BTtransmit**

A boolean used by the PCS Transmit Process to indicate whether a frame transmission is in progress. Used by Carrier Sense process.

Values: TRUE: The PCS is transmitting a stream  
FALSE: The PCS is not transmitting a stream

**TXD[7:0]**

The TXD<7:0> signal of the GMII as specified in 35.2.2.4.

**tx\_enable**

The tx\_enable parameter generated by PCS Transmit as specified in Figure 40–8.

Values: TRUE or FALSE

**tx\_error**

The tx\_error parameter generated by PCS Transmit as specified in Figure 40–8.

Values: TRUE or FALSE

**TX\_EN**

The TX\_EN signal of the GMII as specified in 35.2.2.3.

**TX\_ER**

The TX\_ER signal of the GMII as specified in 35.2.2.5.

**tx\_mode**

The tx\_mode parameter set by the PMA PHY Control function and passed to the PCS via the PMA\_TXMODE.indicate primitive.

Values: SEND\_Z, SEND\_N, or SEND\_I

**T<sub>x<sub>n</sub></sub>**

Alias for tx\_symb\_vector at time n.

**tx\_symb\_vector**

A vector of four quinary symbols generated by the PCS Transmit function and passed to the PMA via the PMA\_UNITDATA.request primitive.

Value: SYMB\_4D

**xmt\_err**

A vector of four quinary symbols corresponding to a transmit error indication during normal data transmission or reception, as specified in 40.3.1.3.

**40.3.3.2 Functions****check\_end**

A function used by the PCS Receive process to detect the reception of valid ESD symbols. The check\_end function operates on the next two rx\_symb\_vectors, (R<sub>x<sub>n+1</sub></sub>) and (R<sub>x<sub>n+2</sub></sub>), available via PMA\_UNITDATA.indicate, and returns a boolean value indicating whether these two consecutive vectors contain symbols corresponding to a legal ESD encoding or not, as specified in 40.3.1.3.

**check\_idle**

A function used by the PCS Receive process to detect the reception of valid idle code-groups after an error condition during the process. The check\_idle function operates on the current rx\_symb\_vector and the next three rx\_symb\_vectors available via PMA\_UNITDATA.indicate and returns a boolean value indicating whether the four consecutive vectors contain symbols corresponding to the idle mode encoding or not, as specified in 40.3.1.3.

**DECODE**

In the PCS Receive process, this function takes as its argument the value of `rx_symb_vector` and returns the corresponding GMII RXD<7:0> octet. DECODE follows the rules outlined in 40.2.6.1.

**ENCODE**

In the PCS Transmit process, this function takes as its argument GMII TXD <7:0> and returns the corresponding `tx_symb_vector`. ENCODE follows the rules outlined in 40.2.5.1.

**40.3.3.3 Timer****symb\_timer**

Continuous timer: The condition `symb_timer_done` becomes true upon timer expiration.

Restart time: Immediately after expiration; timer restart resets the condition `symb_timer_done`.

Duration: 8 ns nominal. (See clock tolerance in 40.6.1.2.6.)

Symb-timer shall be generated synchronously with TX\_TCLK. In the PCS Transmit state diagram, the message `PMA_UNITDATA.request` is issued concurrently with `symb_timer_done`.

**40.3.3.4 Messages****PMA\_UNITDATA.indicate (rx\_symb\_vector)**

A signal sent by PMA Receive indicating that a vector of four quinary symbols is available in `rx_symb_vector`. (See 40.2.6.)

**PMA\_UNITDATA.request (tx\_symb\_vector)**

A signal sent to PMA Transmit indicating that a vector of four quinary symbols is available in `tx_symb_vector`. (See 40.2.5.)

**PUDI**

Alias for `PMA_UNITDATA.indicate (rx_symb_vector)`.

**PUDR**

Alias for `PMA_UNITDATA.request (tx_symb_vector)`.

**STD**

Alias for `symb_timer_done`.

#### 40.3.4 State diagrams

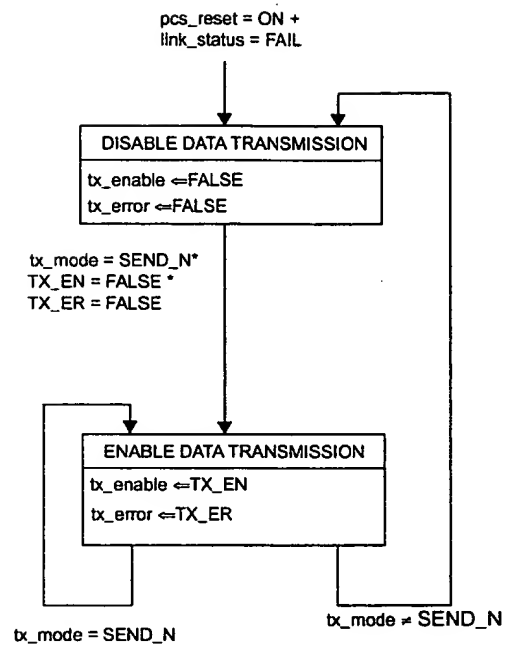


Figure 40–8—PCS Data Transmission Enabling state diagram



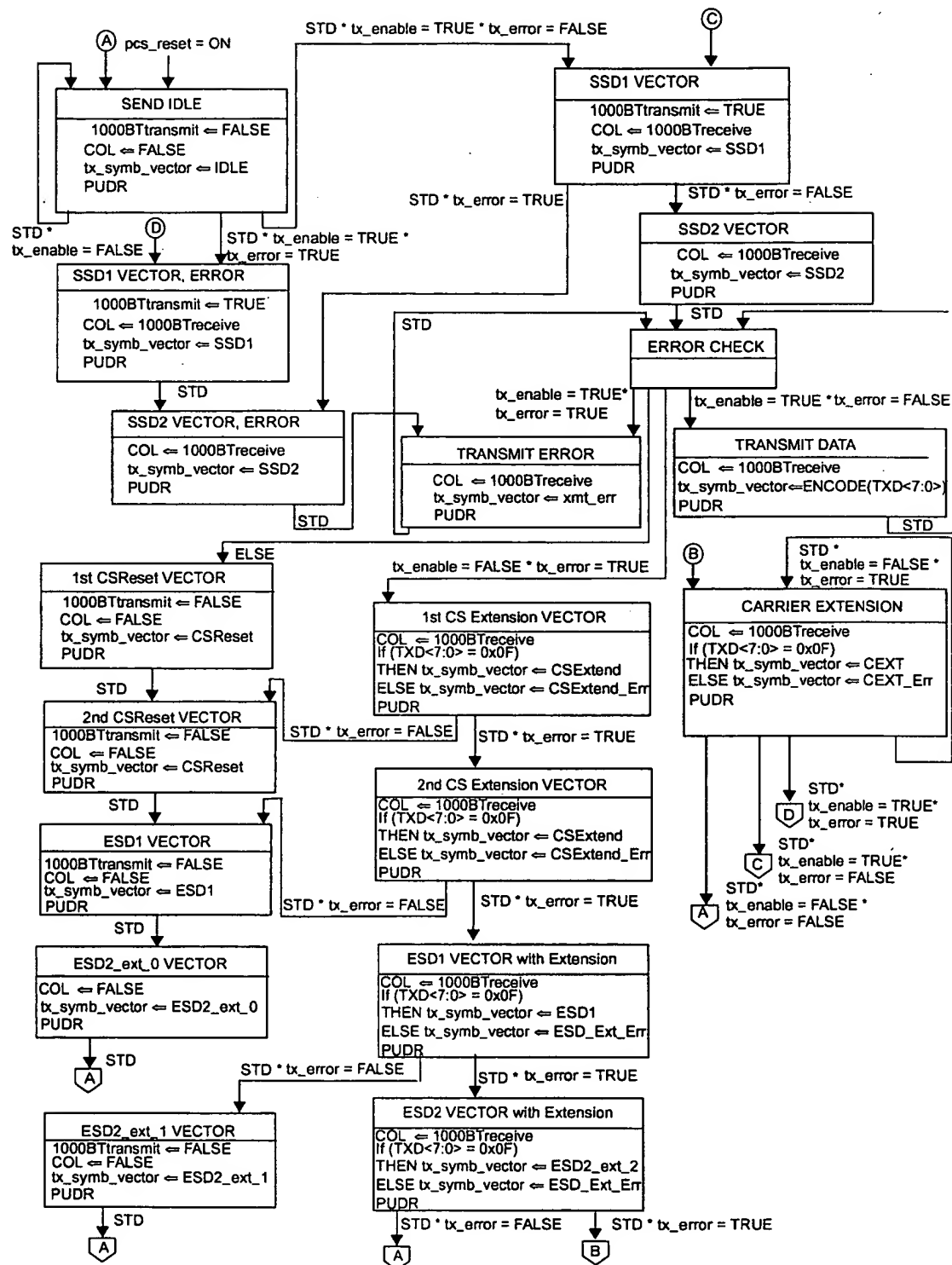
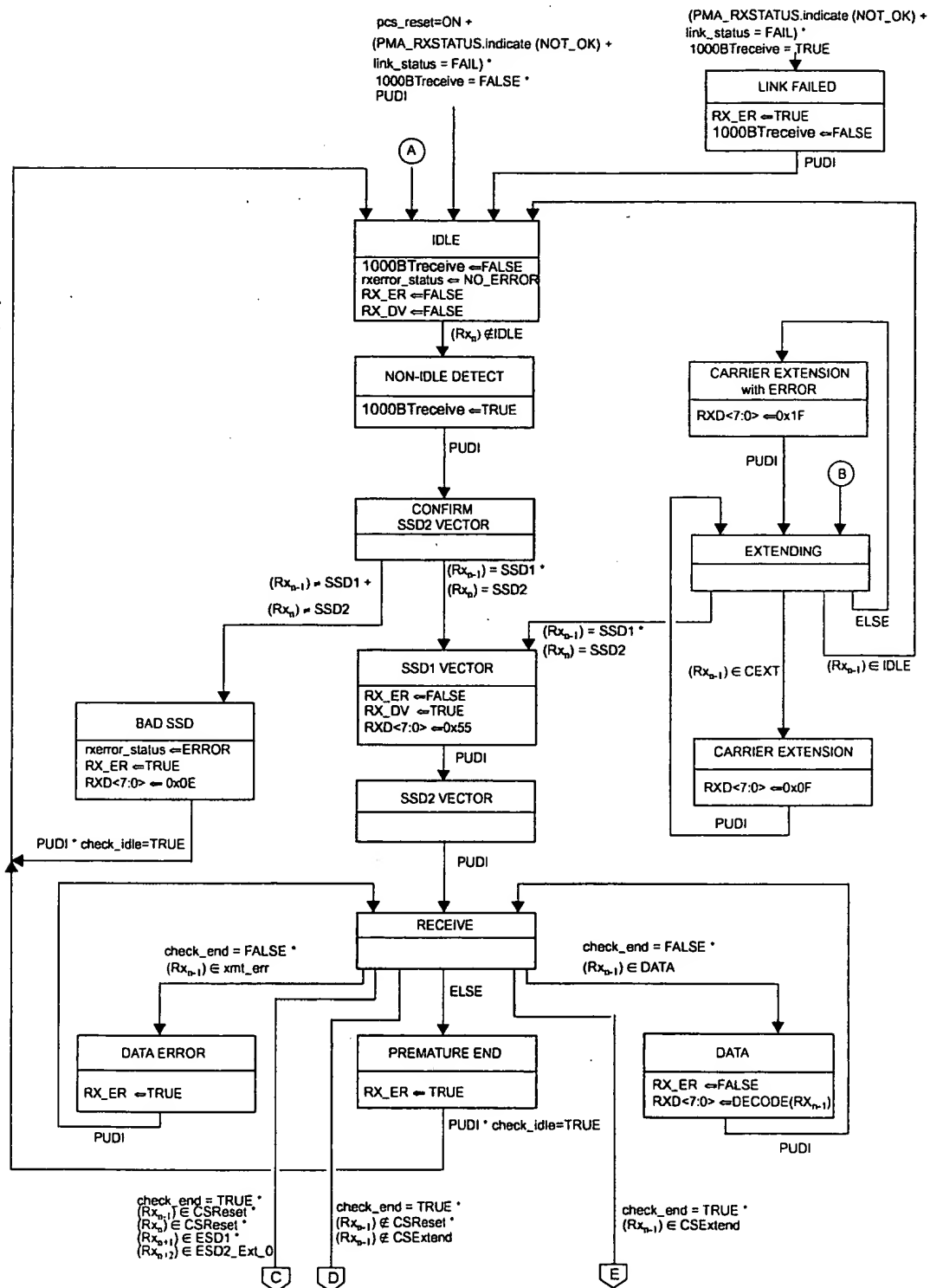
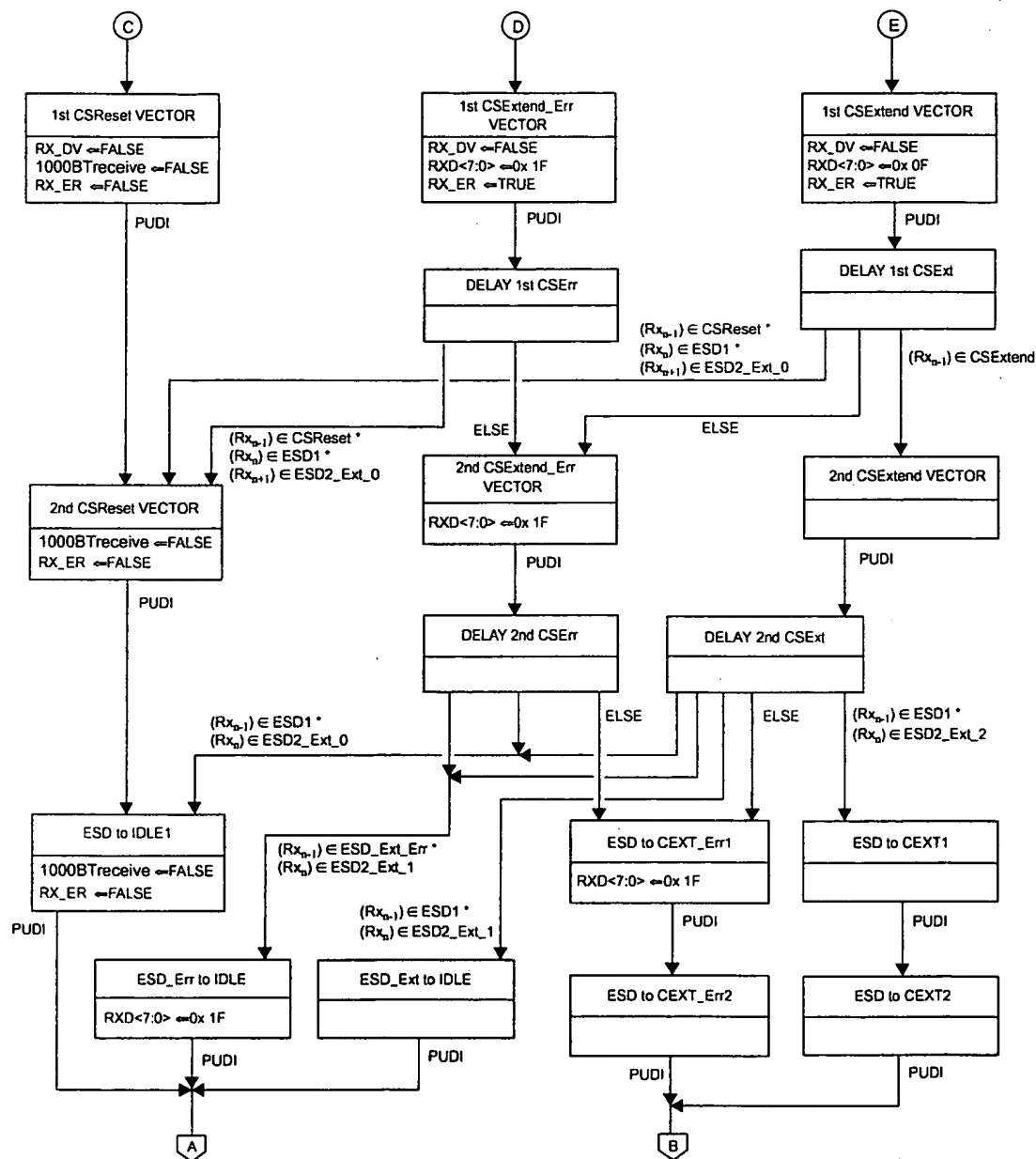


Figure 40-9—PCS Transmit state diagram



**Figure 40–10a—PCS Receive state diagram, part a**



**Figure 40–10b—PCS Receive state diagram, part b**

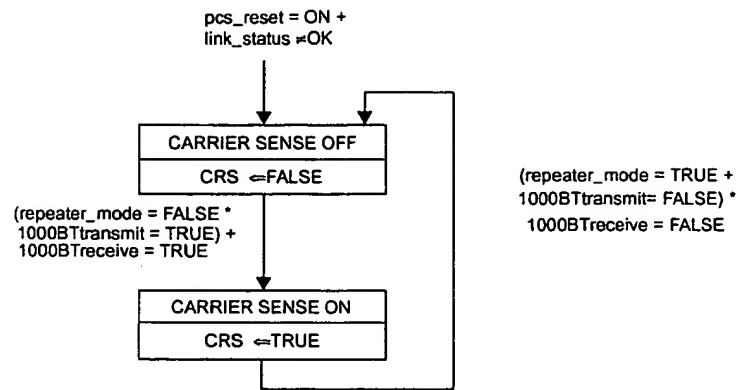


Figure 40–11—PCS Carrier Sense state diagram

#### 40.3.4.1 Supplement to state diagram

Figure 40–12 reiterates the information shown in Figure 40–9 in timing diagram format. It is informative only. Time proceeds from left to right in the figure.

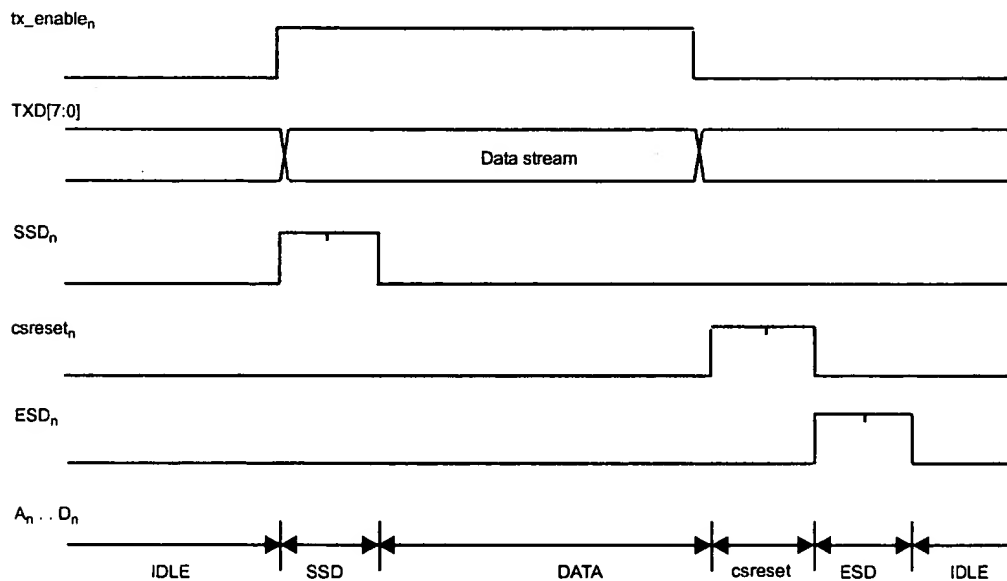


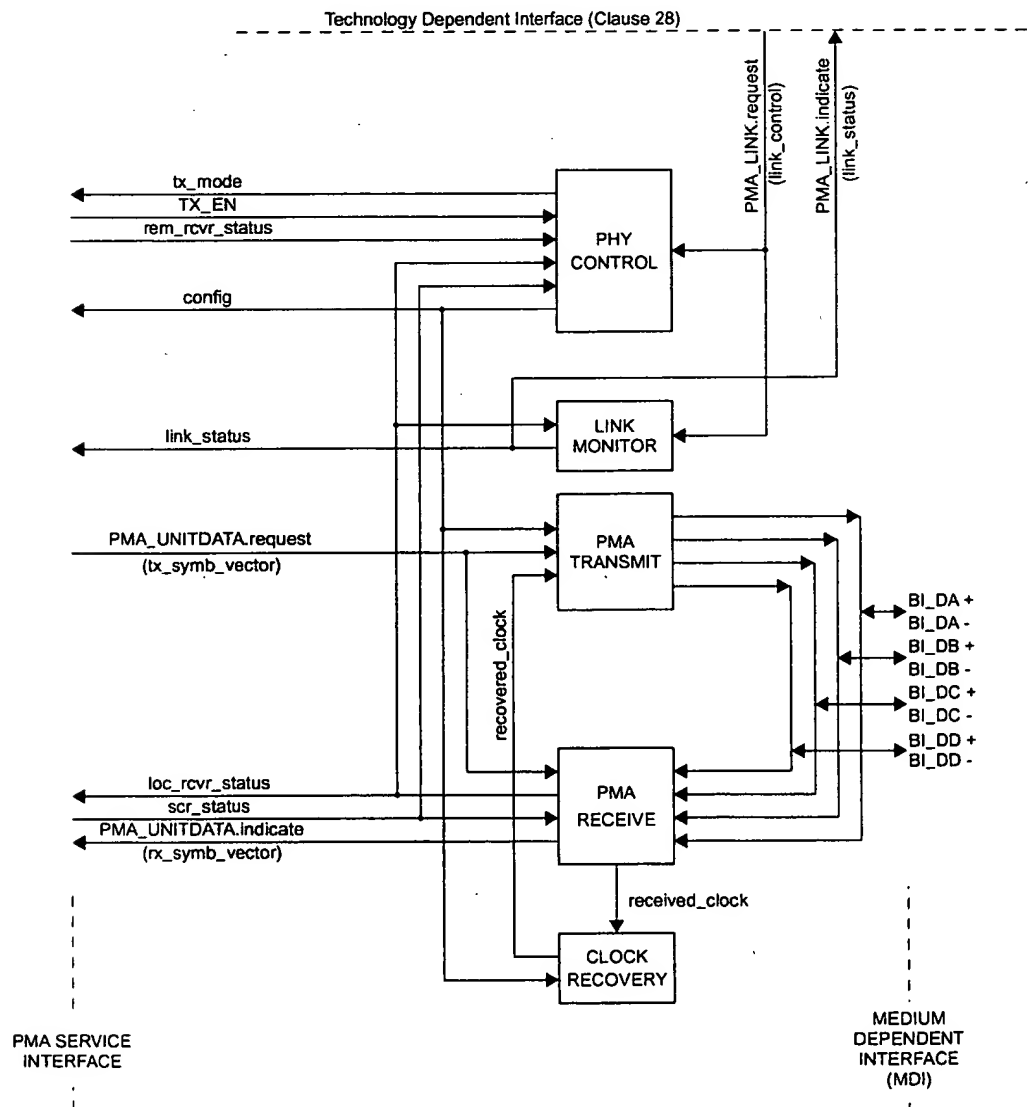
Figure 40–12—PCS sublayer to PMA timing

## 40.4 Physical Medium Attachment (PMA) sublayer

### 40.4.1 PMA functional specifications

The PMA couples messages from a PMA service interface specified in 40.2.2 to the 1000BASE-T baseband medium, specified in 40.7.

The interface between PMA and the baseband medium is the Medium Dependent Interface (MDI), which is specified in 40.8.



NOTE The recovered\_clock arc is shown to indicate delivery of the recovered clock signal back to PMA TRANSMIT for loop timing.

**Figure 40-13—PMA reference diagram**

#### 40.4.2 PMA functions

The PMA sublayer comprises one PMA Reset function and five simultaneous and asynchronous operating functions. The PMA operating functions are PHY Control, PMA Transmit, PMA Receive, Link Monitor, and Clock Recovery. All operating functions are started immediately after the successful completion of the PMA Reset function.

The PMA reference diagram, Figure 40–13, shows how the operating functions relate to the messages of the PMA Service interface and the signals of the MDI. Connections from the management interface, comprising the signals MDC and MDIO, to other layers are pervasive and are not shown in Figure 40–13. The management interface and its functions are specified in Clause 22.

##### 40.4.2.1 PMA Reset function

The PMA Reset function shall be executed whenever one of the two following conditions occur:

- a) Power on (see 36.2.5.1.3)
- b) The receipt of a request for reset from the management entity

PMA Reset sets `pcs_reset=ON` while any of the above reset conditions hold true. All state diagrams take the open-ended `pma_reset` branch upon execution of PMA Reset. The reference diagrams do not explicitly show the PMA Reset function.

##### 40.4.2.2 PMA Transmit function

The PMA Transmit function comprises four synchronous transmitters to generate four 5-level pulse-amplitude modulated signals on each of the four pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD. PMA Transmit shall continuously transmit onto the MDI pulses modulated by the quinary symbols given by `tx_symb_vector[BI_DA]`, `tx_symb_vector[BI_DB]`, `tx_symb_vector[BI_DC]` and `tx_symb_vector[BI_DD]`, respectively. The four transmitters shall be driven by the same transmit clock, TX\_TCLK. The signals generated by PMA Transmit shall follow the mathematical description given in 40.4.3.1, and shall comply with the electrical specifications given in 40.6.

When the `PMA_CONFIG.indicate` parameter `config` is MASTER, the PMA Transmit function shall source TX\_TCLK from a local clock source while meeting the transmit jitter requirements of 40.6.1.2.5. When the `PMA_CONFIG.indicate` parameter `config` is SLAVE, the PMA Transmit function shall source TX\_TCLK from the recovered clock of 40.4.2.6 while meeting the jitter requirements of 40.6.1.2.5.

##### 40.4.2.3 PMA Receive function

The PMA Receive function comprises four independent receivers for quinary pulse-amplitude modulated signals on each of the four pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD. PMA Receive contains the circuits necessary to both detect quinary symbol sequences from the signals received at the MDI over receive pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD and to present these sequences to the PCS Receive function. The signals received at the MDI are described mathematically in 40.4.3.2. The PMA shall translate the signals received on pairs BI\_DA, BI\_DB, BI\_DC, and BI\_DD into the `PMA_UNITDATA.indicate` parameter `rx_symb_vector` with a symbol error rate of less than  $10^{-10}$  over a channel meeting the requirements of 40.7.

To achieve the indicated performance, it is highly recommended that PMA Receive include the functions of signal equalization, echo and crosstalk cancellation, and sequence estimation. The sequence of code-groups assigned to `tx_symb_vector` is needed to perform echo and self near-end crosstalk cancellation.

The PMA Receive function uses the `scr_status` parameter and the state of the equalization, cancellation, and estimation functions to determine the quality of the receiver performance, and generates the `loc_rcvr_status` variable accordingly. The precise algorithm for generation of `loc_rcvr_status` is implementation dependent.

#### 40.4.2.4 PHY Control function

PHY Control generates the control actions that are needed to bring the PHY into a mode of operation during which frames can be exchanged with the link partner. PHY Control shall comply with the state diagram description given in Figure 40–15.

During Auto-Negotiation PHY Control is in the DISABLE 1000BASE-T TRANSMITTER state and the transmitters are disabled. When the Auto-Negotiation process asserts `link_control=ENABLE`, PHY Control enters the SLAVE SILENT state. Upon entering this state, the `maxwait_timer` is started and PHY Control forces transmission of zeros by setting `tx_mode=SEND_Z`. The transition out of the SLAVE SILENT state depends on whether the PHY is operating in MASTER or SLAVE mode. In MASTER mode, PHY Control transitions immediately to the TRAINING state. In SLAVE mode, PHY Control transitions to the TRAINING state only after the SLAVE PHY converges its decision feedback equalizer (DFE), acquires timing, and acquires its descrambler state, and sets `scr_status=OK`.

For the SLAVE PHY, the final convergence of the adaptive filter parameters is completed in the TRAINING state. The MASTER PHY performs all its receiver convergence functions in the TRAINING state. Upon entering the TRAINING state, the `minwait_timer` is started and PHY Control forces transmission into the idle mode by asserting `tx_mode=SEND_I`. After the PHY completes successful training and establishes proper receiver operations, PCS Transmit conveys this information to the link partner via transmission of the parameter `loc_rcvr_status`. (See  $Sd_n[2]$  in 40.3.1.3.4.) The link partner's value for `loc_rcvr_status` is stored in the local device parameter `rem_rcvr_status`. When the `minwait_timer` expires and the condition `loc_rcvr_status=OK` is satisfied, PHY Control transitions into either the SEND IDLE OR DATA state if `rem_rcvr_status=OK` or the SEND IDLE state if `rem_rcvr_status=NOT_OK`. On entry into either the SEND IDLE or SEND IDLE OR DATA states, the `maxwait_timer` is stopped and the `minwait_timer` is started.

The normal mode of operation corresponds to the SEND IDLE OR DATA state, where PHY Control asserts `tx_mode=SEND_N` and transmission of data over the link can take place. In this state, when no frames have to be sent, idle transmission takes place.

If unsatisfactory receiver operation is detected in the SEND IDLE OR DATA or SEND IDLE states (`loc_rcvr_status=NOT_OK`) and the `minwait_timer` has expired, transmission of the current frame is completed and PHY Control enters the SLAVE SILENT state. In the SEND IDLE OR DATA state, whenever a PHY that operates reliably detects unsatisfactory operation of the remote PHY (`rem_rcvr_status=NOT_OK`) and the `minwait_timer` has expired, it enters the SEND IDLE state where `tx_mode=SEND_I` is asserted and idle transmission takes place. In this state, encoding is performed with the parameter `loc_rcvr_status=OK`. As soon as the remote PHY signals satisfactory receiver operation (`rem_rcvr_status=OK`) and the `minwait_timer` has expired, the SEND IDLE OR DATA state is entered.

PHY Control may force the transmit scrambler state to be initialized to an arbitrary value by requesting the execution of the PCS Reset function defined in 40.3.1.1.

#### 40.4.2.5 Link Monitor function

Link Monitor determines the status of the underlying receive channel and communicates it via the variable `link_status`. Failure of the underlying receive channel typically causes the PMA's clients to suspend normal operation.

The Link Monitor function shall comply with the state diagram of Figure 40–16.

Upon power on, reset, or release from power down, the Auto-Negotiation algorithm sets `link_control=SCAN_FOR_CARRIER` and, during this period, sends fast link pulses to signal its presence to a remote station. If the presence of a remote station is sensed through reception of fast link pulses, the Auto-Negotiation algorithm sets `link_control=DISABLE` and exchanges Auto-Negotiation information with the remote station. During this period, `link_status=FAIL` is asserted. If the presence of a remote 1000BASE-T station is established, the Auto-Negotiation algorithm permits full operation by setting `link_control=ENABLE`. As soon as reliable transmission is achieved, the variable `link_status=OK` is asserted, upon which further PHY operations can take place.

#### 40.4.2.6 Clock Recovery function

The Clock Recovery function couples to all four receive pairs. It may provide independent clock phases for sampling the signals on each of the four pairs.

The Clock Recovery function shall provide clocks suitable for signal sampling on each line so that the symbol-error rate indicated in 40.4.2.3 is achieved. The received clock signal must be stable and ready for use when training has been completed (`loc_rcvr_status=OK`). The received clock signal is supplied to the PMA Transmit function by `received_clock`.

#### 40.4.3 MDI

Communication through the MDI is summarized in 40.4.3.1 and 40.4.3.2.

##### 40.4.3.1 MDI signals transmitted by the PHY

The quinary symbols to be transmitted by the PMA on the four pairs `BI_DA`, `BI_DB`, `BI_DC`, and `BI_DD` are denoted by `tx_symb_vector[BI_DA]`, `tx_symb_vector[BI_DB]`, `tx_symb_vector[BI_DC]`, and `tx_symb_vector[BI_DD]`, respectively. The modulation scheme used over each pair is 5-level Pulse Amplitude Modulation. PMA Transmit generates a pulse-amplitude modulated signal on each pair in the following form:

$$s(t) = \sum_k a_k h_1(t - kT)$$

In the above equation,  $a_k$  represents the quinary symbol from the set  $\{2, 1, 0, -1, -2\}$  to be transmitted at time  $kT$ , and  $h_1(t)$  denotes the system symbol response at the MDI. This symbol response shall comply with the electrical specifications given in 40.6.

##### 40.4.3.2 Signals received at the MDI

Signals received at the MDI can be expressed for each pair as pulse-amplitude modulated signals that are corrupted by noise as follows:

$$r(t) = \sum_k a_k h_2(t - kT) + w(t)$$

In this equation,  $h_2(t)$  denotes the impulse response of the overall channel between the transmit symbol source and the receive MDI and  $w(t)$  is a term that represents the contribution of various noise sources. The four signals received on pairs `BI_DA`, `BI_DB`, `BI_DC`, and `BI_DD` shall be processed within the PMA Receive function to yield the quinary received symbols `rx_symb_vector[BI_DA]`, `rx_symb_vector[BI_DB]`, `rx_symb_vector[BI_DC]`, and `rx_symb_vector[BI_DD]`.



#### 40.4.4 Automatic MDI/MDI-X Configuration

Automatic MDI/MDI-X Configuration is intended to eliminate the need for crossover cables between similar devices. Implementation of an automatic MDI/MDI-X configuration is optional for 1000BASE-T devices. If an automatic configuration method is used, it shall comply with the following specifications. The assignment of pin-outs for a 1000BASE-T crossover function cable is shown in Table 40–12 in 40.8.

##### 40.4.4.1 Description of Automatic MDI/MDI-X state machine

The Automatic MDI/MDI-X state machine facilitates switching the BI\_DA(C)+ and BI\_DA(C)– with the BI\_DB(D)+ and BI\_DB(D)– signals respectively prior to the auto-negotiation mode of operation so that FLPs can be transmitted and received in compliance with Clause 28 Auto-Negotiation specifications. The correct polarization of the crossover circuit is determined by an algorithm that controls the switching function. This algorithm uses an 11-bit Linear Feedback Shift Register (LFSR) to create a pseudo-random sequence that each end of the link uses to determine its proposed configuration. Upon making the selection to either MDI or MDI-X, the node waits for a specified amount of time while evaluating its receive channel to determine whether the other end of the link is sending link pulses or PHY-dependent data. If link pulses or PHY-dependent data are detected, it remains in that configuration. If link pulses or PHY-dependent data are not detected, it increments its LFSR and makes a decision to switch based on the value of the next bit. The state machine does not move from one state to another while link pulses are being transmitted.

##### 40.4.4.2 Pseudo-random sequence generator

One possible implementation of the pseudo-random sequence generator using a linear-feedback shift register is shown in Figure 40–14. The bits stored in the shift register delay line at time  $n$  are denoted by  $S[10:0]$ . At each sample period, the shift register is advanced by one bit and one new bit represented by  $S[0]$  is generated. Switch control is determined by  $S[10]$ .

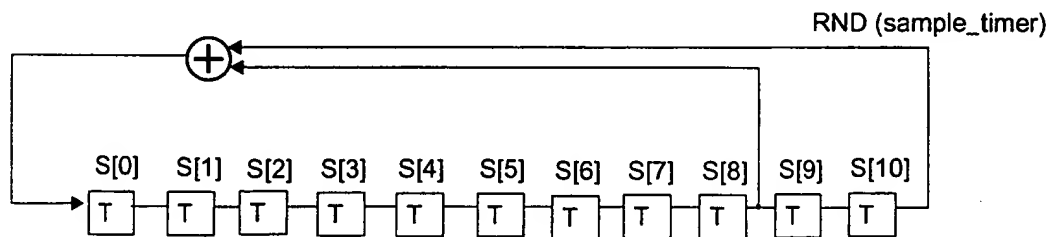


Figure 40–14—Automatic MDI/MDI-X linear-feedback shift register

#### 40.4.5 State variables

##### 40.4.5.1 State diagram variables

config

The PMA shall generate this variable continuously and pass it to the PCS via the PMA\_CONFIG.indicate primitive.

Values: MASTER or SLAVE

link\_control

This variable is defined in 28.2.6.2.

**Link\_Det**

This variable indicates linkpulse = true or link\_status = READY has occurred at the receiver since the last time sample\_timer has been started.

Values: TRUE: linkpulse = true or link\_status = READY has occurred since the last time sample\_timer has been started.

FALSE: otherwise

**linkpulse**

This variable is defined in 28.2.6.3.

**link\_status**

This variable is defined in 28.2.6.1.

**loc\_rcvr\_status**

Variable set by the PMA Receive function to indicate correct or incorrect operation of the receive link for the local PHY.

Values: OK: The receive link for the local PHY is operating reliably.

NOT\_OK: Operation of the receive link for the local PHY is unreliable.

**MDI\_Status**

This variable defines the condition of the Automatic MDI/MDI-X physical connection.

Values: MDI: The BI\_DA, BI\_DB, BI\_DC, and BI\_DD pairs follow the connections as described in the MDI column of Table 40–12.

MDI-X: The BI\_DA, BI\_DB, BI\_DC, and BI\_DD pairs follow the connections as described in the MDI-X column of Table 40–12.

**pma\_reset**

Allows reset of all PMA functions.

Values: ON or OFF

Set by: PMA Reset

**rem\_rcvr\_status**

Variable set by the PCS Receive function to indicate whether correct operation of the receive link for the remote PHY is detected or not.

Values: OK: The receive link for the remote PHY is operating reliably.

NOT\_OK: Reliable operation of the receive link for the remote PHY is not detected.

**RND (sample\_timer)**

This variable is defined as bit S[10] of the LSFR described in 40.4.4.2

**scr\_status**

The scr\_status parameter as communicated by the PMA\_SCRSTATUS.request primitive.

Values: OK: The descrambler has achieved synchronization.

NOT\_OK: The descrambler is not synchronized.

**T\_Pulse**

This variable indicates that a linkpulse is being transmitted to the MDI.

Values: TRUE: Pulse being transmitted to the MDI

FALSE: Otherwise

**tx\_enable**

The tx\_enable parameter generated by PCS Transmit as specified in Figure 40–8.

Values: TRUE or FALSE as per 40.3.3.1.

**tx\_mode**

PCS Transmit sends code-groups according to the value assumed by this variable.

Values: SEND\_N: This value is continuously asserted when transmission of sequences of code-groups representing a GMII data stream, control information, or idle mode is to take place.

SEND\_I: This value is continuously asserted when transmission of sequences of code-groups representing the idle mode is to take place.

SEND\_Z: This value is asserted when transmission of zero code-groups is to take place.

**40.4.5.2 Timers**

All timers operate in the manner described in 14.2.3.2 with the following addition. A timer is reset and stops counting upon entering a state where “stop timer” is asserted.

**A\_timer**

An asynchronous (to the Auto-Crossover State Machine) free-running timer that provides for a relatively arbitrary reset of the state machine to its initial state. This timer is used to reduce the probability of a lock-up condition where both nodes have the same identical seed initialization at the same point in time.

Values: The condition A\_timer\_done becomes true upon timer expiration.

Duration: This timer shall have a period of  $1.3 \text{ s} \pm 25\%$ .

Initialization of A\_timer is implementation specific.

**maxwait\_timer**

A timer used to limit the amount of time during which a receiver dwells in the SLAVE SILENT and TRAINING states. The timer shall expire  $750 \pm 10 \text{ ms}$  if config = MASTER or  $350 \pm 5 \text{ ms}$  if config = SLAVE. This timer is used jointly in the PHY Control and Link Monitor state diagrams. The maxwait\_timer is tested by the Link Monitor to force link\_status to be set to FAIL if the timer expires and loc\_rcvr\_status is NOT\_OK. See Figure 40–15.

**minwait\_timer**

A timer used to determine the minimum amount of time the PHY Control stays in the TRAINING, SEND IDLE, or DATA states. The timer shall expire  $1 \pm 0.1 \mu\text{s}$  after being started.

**sample\_timer**

This timer provides a long enough sampling window to ensure detection of Link Pulses or link\_status, if they exist at the receiver.

Values: The condition sample\_timer\_done becomes true upon timer expiration.

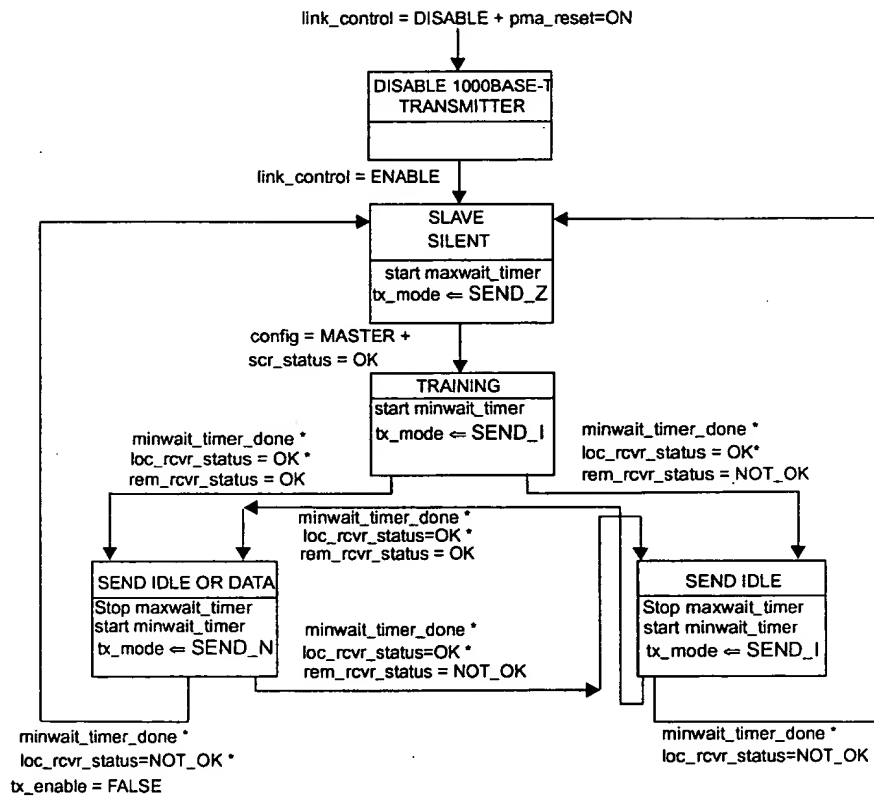
Duration: This timer shall have a period of  $62 \pm 2 \text{ ms}$ .

**stabilize\_timer**

A timer used to control the minimum time that loc\_rcvr\_status must be OK before a transition to Link Up can occur. The timer shall expire  $1 \pm 0.1 \mu\text{s}$  after being started.

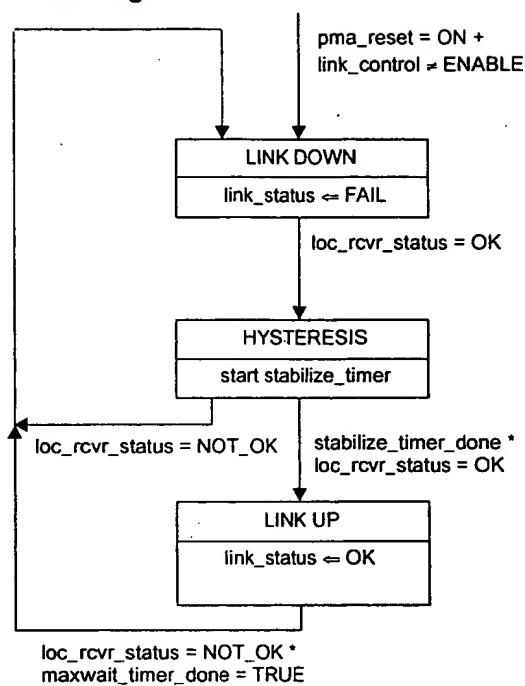
### 40.4.6 State Diagrams

#### 40.4.6.1 PHY Control state diagram



**Figure 40–15—PHY Control state diagram**

## 40.4.6.2 Link Monitor state diagram



## NOTES

- 1 maxwait\_timer is started in PHY Control state diagram (see Figure 40—15).
- 2 The variables link\_control and link\_status are designated as link\_control\_(1GigT) and link\_status\_(1GigT), respectively, by the Auto-Negotiation Arbitration state diagram (Figure 28—16)

Figure 40—16—Link Monitor state diagram

#### 40.4.6.2.1 Auto Crossover state diagram

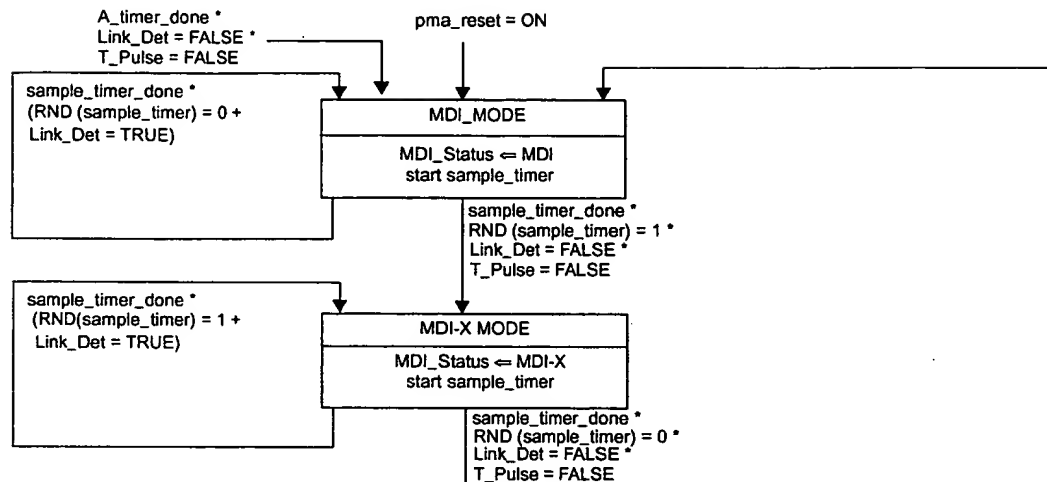


Figure 40–17—Auto Crossover state diagram

### 40.5 Management interface

1000BASE-T makes extensive use of the management functions provided by the MII Management Interface (see 22.2.4), and the communication and self-configuration functions provided by Auto-Negotiation (Clause 28.)

#### 40.5.1 Support for Auto-Negotiation

All 1000BASE-T PHYs shall provide support for Auto-Negotiation (Clause 28) and shall be capable of operating as MASTER or SLAVE.

Auto-Negotiation is performed as part of the initial set-up of the link, and allows the PHYs at each end to advertise their capabilities (speed, PHY type, half or full duplex) and to automatically select the operating mode for communication on the link. Auto-negotiation signaling is used for the following two primary purposes for 1000BASE-T:

- To negotiate that the PHY is capable of supporting 1000BASE-T half duplex or full duplex transmission.
- To determine the MASTER-SLAVE relationship between the PHYs at each end of the link.

This relationship is necessary for establishing the timing control of each PHY. The 1000BASE-T MASTER PHY is clocked from a local source. The SLAVE PHY uses loop timing where the clock is recovered from the received data stream.

### 40.5.1.1 1000BASE-T use of registers during Auto-Negotiation

A 1000BASE-T PHY shall use the management register definitions and values specified in Table 40–3.

**Table 40–3—1000BASE-T Registers**

Register	Bit	Name	Description	Type <sup>a</sup>
0	0.15:0	MII control register	Defined in 28.2.4.1.1	RO
1	1.15:0	MII status register	Defined in 28.2.4.1.2	RO
4	4.15:0	Auto-Negotiation advertisement register	The Selector Field (4.4:0) is set to the appropriate code as specified in Annex 28A. The Technology Ability Field bits 4.12:5 are set to the appropriate code as specified in Annexes 28B and 28D. Bit 4.15 is set to logical one to indicate the desired exchange of Next Pages describing the gigabit extended capabilities.	R/W
5	5.15:0	Auto-Negotiation link partner ability register	Defined in 28.2.4.1.4. 1000BASE-T implementations do not use this register to store Auto-Negotiation Link Partner Next Page data.	RO
6	6.15:0	Auto-Negotiation expansion register	Defined in 28.2.4.1.5	RO
7	7.15:0	Auto-Negotiation Next Page transmit register	Defined in 28.2.4.1.6	R/W
8	8.15:0	Auto-Negotiation link partner Next Page register	Defined in 28.2.4.1.8	RO
9	9.15:13	Test mode bits	Transmitter test mode operations are defined by bits 9.15:13 as described in 40.6.1.1.2 and Table 40–7. The default values for bits 9.15:13 are all zero.	R/W
9	9.12	MASTER-SLAVE Manual Config Enable	1=Enable MASTER-SLAVE Manual configuration value 0=Disable MASTER-SLAVE Manual configuration value Default bit value is 0.	R/W
9	9.11	MASTER-SLAVE Config Value	1=Configure PHY as MASTER during MASTER-SLAVE negotiation, only when 9.12 is set to logical one. 0=Configure PHY as SLAVE during MASTER-SLAVE negotiation, only when 9.12 is set to logical one. Default bit value is 0.	R/W
9	9.10	Port type	Bit 9.10 is to be used to indicate the preference to operate as MASTER (multiport device) or as SLAVE (single-port device) if the MASTER-SLAVE Manual Configuration Enable bit, 9.12, is not set. Usage of this bit is described in 40.5.2. 1=Multiport device 0=single-port device	R/W
9	9.9	1000BASE-T Full Duplex	1 = Advertise PHY is 1000BASE-T full duplex capable. 0 = Advertise PHY is not 1000BASE-T full duplex capable.	R/W
9	9.8	1000BASE-T Half Duplex	1 = Advertise PHY is 1000BASE-T half duplex capable. 0 = Advertise PHY is not 1000BASE-T half duplex capable.	R/W
<sup>a</sup> R/W = Read/Write, RO = Read Only, SC = Self Clearing, LH = Latch High				

Table 40–3—1000BASE-T Registers (*continued*)

Register	Bit	Name	Description	Type <sup>a</sup>
9	9.7:0	Reserved	Write as 0, ignore on read.	R/W
10	10.15	MASTER-SLAVE configuration fault	Configuration fault, as well as the criteria and method of fault detection, is PHY specific. The MASTER-SLAVE Configuration Fault bit will be cleared each time register 10 is read via the management interface and will be cleared by a 1000BASE-T PMA reset. This bit will self clear on Auto-Negotiation enable or Auto-Negotiation complete. This bit will be set if the number of failed MASTER-SLAVE resolutions reaches 7. For 1000BASE-T, the fault condition will occur when both PHYs are forced to be MASTERS or SLAVES at the same time using bits 9.12 and 9.11. Bit 10.15 should be set via the MASTER-SLAVE Configuration Resolution function described in 40.5.2. 1 = MASTER-SLAVE configuration fault detected 0 = No MASTER-SLAVE configuration fault detected	RO/LH/SC
10	10.14	MASTER-SLAVE configuration resolution	1 = Local PHY configuration resolved to MASTER 0 = Local PHY configuration resolved to SLAVE	RO
10	10.13	Local Receiver Status	1 = Local Receiver OK (loc_rcvr_status=OK) 0 = Local Receiver not OK (loc_rcvr_status=NOT_OK) Defined by the value of loc_rcvr_status as per 40.4.5.1.	RO
10	10.12	Remote Receiver Status	1 = Remote Receiver OK (rem_rcvr_status=OK) 0 = Remote Receiver not OK (rem_rcvr_status=NOT_OK) Defined by the value of rem_rcvr_status as per 40.4.5.1.	RO
10	10.11	LP 1000T FD	1 = Link Partner is capable of 1000BASE-T full duplex 0 = Link Partner is not capable of 1000BASE-T full duplex This bit is guaranteed to be valid only when the Page received bit (6.1) has been set to 1.	RO
10	10.10	LP 1000T HD	1 = Link Partner is capable of 1000BASE-T half duplex 0 = Link Partner is not capable of 1000BASE-T half duplex This bit is guaranteed to be valid only when the Page received bit (6.1) has been set to 1.	RO
10	10.9:8	Reserved	Reserved	RO
10	10.7:0	Idle Error Count	Bits 10.7:0 indicate the Idle Error count, where 10.7 is the most significant bit. These bits contain a cumulative count of the errors detected when the receiver is receiving idles and PMA_TXMODE.indicate is equal to SEND_N (indicating that both local and remote receiver status have been detected to be OK). The counter is incremented every symbol period that rxerror_status is equal to ERROR. These bits are reset to all zeros when the error count is read by the management function or upon execution of the PCS Reset function and are to be held at all ones in case of overflow (see 30.5.1.1.11).	RO/SC
15	15.15:12	Extended status register	See 22.2.4.4	RO

<sup>a</sup> R/W = Read/Write, RO = Read Only, SC = Self Clearing, LH = Latch High



### 40.5.1.2 1000BASE-T Auto-Negotiation page use

1000BASE-T PHYs shall exchange one Auto-Negotiation Base Page, a 1000BASE-T formatted Next Page, and two 1000BASE-T unformatted Next Pages in sequence, without interruption, as specified in Table 40–4. Additional Next Pages can be exchanged as described in Annex 40C.

Note that the Acknowledge 2 bit is not utilized and has no meaning when used for the 1000BASE-T message page exchange.

**Table 40–4 — 1000BASE-T Base and Next Pages bit assignments**

Bit	Bit definition	Register location
<b>BASE PAGE</b>		
D15	1 (to indicate that Next Pages follow)	
D14:D1	As specified in 28.2.1.2	Management register 4
<b>PAGE 0 (Message Next Page)</b>		
M10:M0	8	
<b>PAGE 1 (Unformatted Next Page)</b>		
U10:U5	Reserved transmit as 0	
U4	1000BASE-T half duplex (1 = half duplex and 0 = no half duplex)	GMII register 9.8 (MASTER-SLAVE Control register)
U3	1000BASE-T full duplex (1 = full duplex and 0 = no full duplex)	GMII register 9.9 (MASTER-SLAVE Control register)
U2	1000BASE-T port type bit (1 = multiport device and 0 = single-port device)	GMII register 9.10 (MASTER-SLAVE Control register)
U1	1000BASE-T MASTER-SLAVE Manual Configuration value (1 = MASTER and 0 = SLAVE.) This bit is ignored if 9.12 = 0.	GMII register 9.11 (MASTER-SLAVE Control register)
U0	1000BASE-T MASTER-SLAVE Manual Configuration Enable (1 = Manual Configuration Enable.) This bit is intended to be used for manual selection in a particular MASTER-SLAVE mode and is to be used in conjunction with bit 9.11.	GMII register 9.12 (MASTER-SLAVE Control register)
<b>PAGE 2 (Unformatted Next Page)</b>		
U10	1000BASE-T MASTER-SLAVE Seed Bit 10 (SB10) (MSB)	MASTER-SLAVE Seed Value (10:0)
U9	1000BASE-T MASTER-SLAVE Seed Bit 9 (SB9)	
U8	1000BASE-T MASTER-SLAVE Seed Bit 8 (SB8)	
U7	1000BASE-T MASTER-SLAVE Seed Bit 7 (SB7)	
U6	1000BASE-T MASTER-SLAVE Seed Bit 6 (SB6)	
U5	1000BASE-T MASTER-SLAVE Seed Bit 5 (SB5)	
U4	1000BASE-T MASTER-SLAVE Seed Bit 4 (SB4)	
U3	1000BASE-T MASTER-SLAVE Seed Bit 3 (SB3)	
U2	1000BASE-T MASTER-SLAVE Seed Bit 2 (SB2)	
U1	1000BASE-T MASTER-SLAVE Seed Bit 1 (SB1)	
U0	1000BASE-T MASTER-SLAVE Seed Bit 0 (SB0)	

### 40.5.1.3 Sending Next Pages

Implementors who do not wish to send additional Next Pages (i.e., Next Pages in addition to those required to perform PHY configuration as defined in this clause) can use Auto-Negotiation as defined in Clause 28 and the Next Pages defined in 40.5.1.2. Implementors who wish to send additional Next Pages are advised to consult Annex 40C.

### 40.5.2 MASTER-SLAVE configuration resolution

Since both PHYs that share a link segment are capable of being MASTER or SLAVE, a prioritization scheme exists to ensure that the correct mode is chosen. The MASTER-SLAVE relationship shall be determined during Auto-Negotiation using Table 40–5 with the 1000BASE-T Technology Ability Next Page bit values specified in Table 40–4 and information received from the link partner. This process is conducted at the entrance to the FLP LINK GOOD CHECK state shown in the Arbitration state diagram (Figure 28–13.)

The following four equations are used to determine these relationships:

$$\text{manual\_MASTER} = U0 * U1$$

$$\text{manual\_SLAVE} = U0 * !U1$$

$$\text{single-port device} = !U0 * !U2,$$

$$\text{multiport device} = !U0 * U2$$

where

U0 is bit 0 of unformatted page 1,

U1 is bit 1 of unformatted page 1, and

U2 is bit 2 of unformatted page 1 (see Table 40–4).

A 1000BASE-T PHY is capable of operating either as the MASTER or SLAVE. In the scenario of a link between a single-port device and a multiport device, the preferred relationship is for the multiport device to be the MASTER PHY and the single-port device to be the SLAVE. However, other topologies may result in contention. The resolution function of Table 40–5 is defined to handle any relationship conflicts.

**Table 40–5—1000BASE-T MASTER-SLAVE configuration resolution table**

Local device type	Remote device type	Local device resolution	Remote device resolution
single-port device	multiport device	SLAVE	MASTER
single-port device	manual_MASTER	SLAVE	MASTER
manual_SLAVE	manual_MASTER	SLAVE	MASTER
manual_SLAVE	multiport device	SLAVE	MASTER
multiport device	manual_MASTER	SLAVE	MASTER
manual_SLAVE	single-port device	SLAVE	MASTER
multiport device	single-port device	MASTER	SLAVE
multiport device	manual_SLAVE	MASTER	SLAVE

**Table 40–5—1000BASE-T MASTER-SLAVE configuration resolution table (continued)**

Local device type	Remote device type	Local device resolution	Remote device resolution
manual_MASTER	manual_SLAVE	MASTER	SLAVE
manual_MASTER	single-port device	MASTER	SLAVE
single-port device	manual_SLAVE	MASTER	SLAVE
manual_MASTER	multiport device	MASTER	SLAVE
multiport device	multiport device	The device with the higher SEED value is configured as MASTER, otherwise SLAVE.	The device with the higher SEED value is configured as MASTER, otherwise SLAVE.
single-port device	single-port device	The device with the higher SEED value is configured as MASTER, otherwise SLAVE	The device with the higher SEED value is configured as MASTER, otherwise SLAVE.
manual_SLAVE	manual_SLAVE	MASTER-SLAVE configuration fault	MASTER-SLAVE configuration fault
manual_MASTER	manual_MASTER	MASTER-SLAVE configuration fault	MASTER-SLAVE configuration fault

The rationale for the hierarchy illustrated in Table 40–5 is straightforward. A 1000BASE-T multiport device has higher priority than a single-port device to become the MASTER. In the case where both devices are of the same type, e.g., both devices are multiport devices, the device with the higher MASTER-SLAVE seed bits (SB0...SB10), where SB10 is the MSB, shall become the MASTER and the device with the lower seed value shall become the SLAVE. In case both devices have the same seed value, both should assert link\_status\_1GigT=FAIL (as defined in 28.3.1) to force a new cycle through Auto-Negotiation. Successful completion of the MASTER-SLAVE resolution shall be treated as MASTER-SLAVE configuration resolution complete.

The method of generating a random or pseudorandom seed is left to the implementor. The generated random seeds should belong to a sequence of independent, identically distributed integer numbers with a uniform distribution in the range of 0 to  $2^{11}-2$ . The algorithm used to generate the integer should be designed to minimize the correlation between the number generated by any two devices at any given time. A seed counter shall be provided to track the number of seed attempts. The seed counter shall be set to zero at start-up and shall be incremented each time a seed is generated. When MASTER-SLAVE resolution is complete, the seed counter shall be reset to 0 and bit 10.15 shall be set to logical zero. A MASTER-SLAVE resolution fault shall be declared if resolution is not reached after the generation of seven seeds.

The MASTER-SLAVE Manual Configuration Enable bit (control register bit 9.12) and the MASTER-SLAVE Config Value bit (control register bit 9.11) are used to manually set a device to become the MASTER or the SLAVE. In case both devices are manually set to become the MASTER or the SLAVE, this condition shall be flagged as a MASTER-SLAVE Configuration fault condition, thus the MASTER-SLAVE Configuration fault bit (status register bit 10.15) shall be set to logical one. The MASTER-SLAVE Configuration fault condition shall be treated as MASTER-SLAVE configuration resolution complete and link\_status\_1GigT shall be set to FAIL, because the MASTER-SLAVE relationship was not resolved. This will force a new cycle through Auto-Negotiation after the link\_fail\_inhibit\_timer has expired. Determination of MASTER-SLAVE values occur on the entrance to the FLP LINK GOOD CHECK state (Figure 28–16) when the highest common denominator (HCD) technology is 1000BASE-T. The resulting MASTER-SLAVE value is used by the 1000BASE-T PHY control (40.4.2.4).

If MASTER-SLAVE Manual Configuration is disabled (bit 9.12 is set to 0) and the local device detects that both the local device and the remote device are of the same type (either multiport device or single-port device) and that both have generated the same random seed, it generates and transmits a new random seed for MASTER-SLAVE negotiation by setting link\_status to FAIL and cycling through the Auto-Negotiation process again.

The MASTER-SLAVE configuration process returns one of the three following outcomes:

- a) *Successful*: Bit 10.15 of the 1000BASE-T Status Register is set to logical zero and bit 10.14 is set to logical one for MASTER resolution or for logical zero for SLAVE resolution. 1000BASE-T returns control to Auto\_Negotiation (at the entrance to the FLP LINK GOOD CHECK state in Figure 28–16) and passes the value MASTER or SLAVE to PMA\_CONFIG.indicate (see 40.2.4.)
- b) *Unsuccessful*: link\_status\_1GigT is set to FAIL and Auto-Negotiation restarts (see Figure 28–16.)
- c) *Fault detected*: (This happens when both end stations are set for manual configuration and both are set to MASTER or both are set to SLAVE.) Bit 10.15 of the 1000BASE-T Status Register is set to logical one to indicate that a configuration fault has been detected. This bit also is set when seven attempts to configure the MASTER SLAVE relationship via the seed method have failed. When a fault is detected, link\_status\_1GigT is set to FAIL, causing Auto-Negotiation to cycle through again.

NOTE—MASTER-SLAVE arbitration only occurs if 1000BASE-T is selected as the highest common denominator; otherwise, it is assumed to have passed this condition.

## 40.6 PMA electrical specifications

This subclause defines the electrical characteristics of the PMA.

Common-mode tests use the common-mode return point as a reference.

### 40.6.1 PMA-to-MDI interface tests

#### 40.6.1.1 Isolation requirement

The PHY shall provide electrical isolation between the port device circuits, including frame ground (if any) and all MDI leads. This electrical separation shall withstand at least one of the following electrical strength tests:

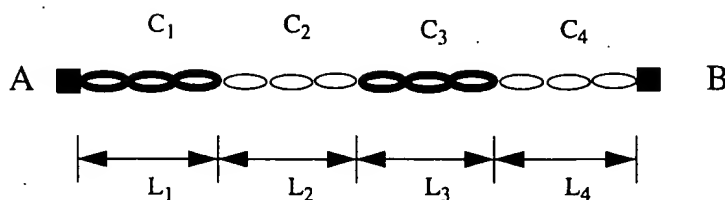
- a) 1500 V rms at 50 Hz to 60 Hz for 60 s, applied as specified in Section 5.3.2 of IEC 60950: 1991.
- b) 2250 Vdc for 60 s, applied as specified in Section 5.3.2 of IEC 60950: 1991.
- c) A sequence of ten 2400 V impulses of alternating polarity, applied at intervals of not less than 1 s. The shape of the impulses shall be 1.2/50  $\mu$ s (1.2  $\mu$ s virtual front time, 50  $\mu$ s virtual time or half value), as defined in IEC 60060.

There shall be no insulation breakdown, as defined in Section 5.3.2 of IEC 60950: 1991, during the test. The resistance after the test shall be at least 2 M $\Omega$ , measured at 500 Vdc.

#### 40.6.1.1.1 Test channel

To perform the transmitter MASTER-SLAVE timing jitter tests described in this clause, a test channel is required to ensure that jitter is measured under conditions of poor signal to echo ratio. This test channel shall be constructed by combining 100 and 120  $\Omega$  cable segments that both meet or exceed ISO/IEC 11801 Category 5 specifications for each pair, as shown in Figure 40–18, with the lengths and additional restrictions on parameters described in Table 40–6. The ends of the test channel shall be terminated with connectors meeting or exceeding ANSI/TIA/EIA-568-A:1995 or ISO/IEC 11801:1995 Category 5 specifications. The

return loss of the resulting test channel shall meet the return loss requirements of 40.7.2.3 and the crosstalk requirements of 40.7.3.



Identical for each of the four pairs.

Figure 40-18—Test channel topology for each cable pair

Table 40-6—Test channel cable segment specifications

Cable segment	Length (meters)	Characteristic impedance (at frequencies > 1 MHz)	Attenuation (per 100 meters at 31.25 MHz)
1	$L_1=1.20$	$120 \pm 5\Omega$	7.8 to 8.8 dB
2	$L_2=x$	$100 \pm 5\Omega$	10.8 to 11.8 dB
3	$L_3=1.48$	$120 \pm 5\Omega$	7.8 to 8.8 dB
4	$L_4=y$	$100 \pm 5\Omega$	10.8 to 11.8 dB

NOTE— $x$  is chosen so that the total delay of segments C1, C2, and C3, averaged across all pairs, is equal to 570 ns at 31.25 MHz; however, if this would cause the total attenuation of segments C1, C2, and C3, averaged across all pairs, to exceed the worst case insertion loss specified in 40.7.2.1 then  $x$  is chosen so that the total attenuation of segments C1, C2, and C3, averaged across all pairs, does not violate 40.7.2.1 at any frequencies. The value of  $y$  is chosen so that the total attenuation of segments C1, C2, C3, and C4, averaged across all pairs, does not violate 40.7.2.1 at any frequency ( $y$  may be 0).

#### 40.6.1.1.2 Test modes

The test modes described below shall be provided to allow for testing of the transmitter waveform, transmitter distortion, and transmitted jitter.

For a PHY with a GMII interface, these modes shall be enabled by setting bits 9.13:15 (1000BASE-T Control Register) of the GMII Management register set as shown in Table 40-7. These test modes shall only change the data symbols provided to the transmitter circuitry and shall not alter the electrical and jitter characteristics of the transmitter and receiver from those of normal (non-test mode) operation. PHYs without a GMII shall provide a means to enable these modes for conformance testing.

**Table 40–7—GMII management register settings for test modes**

Bit 1 (9.15)	Bit 2 (9.14)	Bit 3 (9.13)	Mode
0	0	0	Normal operation
0	0	1	Test mode 1—Transmit waveform test
0	1	0	Test mode 2—Transmit jitter test in MASTER mode
0	1	1	Test mode 3—Transmit jitter test in SLAVE mode
1	0	0	Test mode 4—Transmitter distortion test
1	0	1	Reserved, operations not identified.
1	1	0	Reserved, operations not identified.
1	1	1	Reserved, operations not identified.

When test mode 1 is enabled, the PHY shall transmit the following sequence of data symbols  $A_n$ ,  $B_n$ ,  $C_n$ ,  $D_n$ , of 40.3.1.3.6 continually from all four transmitters:

{+2 followed by 127 0 symbols}, {−2 followed by 127 0 symbols}, {+1 followed by 127 0 symbols}, {−1 followed by 127 0 symbols}, {128 +2 symbols, 128 −2 symbols, 128 +2 symbols, 128 −2 symbols}, {1024 0 symbols}}

This sequence is repeated continually without breaks between the repetitions when the test mode is enabled. A typical transmitter output is shown in Figure 40–19. The transmitter shall time the transmitted symbols from a 125.00 MHz  $\pm$  0.01% clock in the MASTER timing mode.

When test mode 2 is enabled, the PHY shall transmit the data symbol sequence {+2, −2} repeatedly on all channels. The transmitter shall time the transmitted symbols from a 125.00 MHz  $\pm$  0.01% clock in the MASTER timing mode.

When test mode 3 is enabled, the PHY shall transmit the data symbol sequence {+2, −2} repeatedly on all channels. The transmitter shall time the transmitted symbols from a 125.00 MHz  $\pm$  0.01% clock in the SLAVE timing mode. A typical transmitter output for transmitter test modes 2 and 3 is shown in Figure 40–20.

When test mode 4 is enabled, the PHY shall transmit the sequence of symbols generated by the following scrambler generator polynomial, bit generation, and level mappings:

$$g_{s1} = 1 + x^9 + x^{11}$$

The maximum-length shift register used to generate the sequences defined by this polynomial shall be updated once per symbol interval (8 ns). The bits stored in the shift register delay line at a particular time  $n$  are denoted by  $Scr_n[10:0]$ . At each symbol period the shift register is advanced by one bit and one new bit represented by  $Scr_n[0]$  is generated. Bits  $Scr_n[8]$  and  $Scr_n[10]$  are exclusive OR'd together to generate the next  $Scr_n[0]$  bit. The bit sequences,  $x0_n$ ,  $x1_n$ , and  $x2_n$ , generated from combinations of the scrambler bits as shown in the following equations, shall be used to generate the quinary symbols,  $s_n$ , as shown in Table 40–8. The quinary symbol sequence shall be presented simultaneously to all transmitters. The transmitter shall time the transmitted symbols from a 125.00 MHz  $\pm$  0.01% clock in the MASTER timing mode. A typical transmitter output for transmitter test mode 4 is shown in Figure 40–21.

$$x0_n = Scr_n[0]$$

$$x1_n = Scr_n[1] \wedge Scr_n[4]$$

$$x2_n = Scr_n[2] \wedge Scr_n[4]$$

Table 40–8—Transmitter test mode 4 symbol mapping

x2n	x1n	x0n	quinary symbol, $s_n$
0	0	0	0
0	0	1	1
0	1	0	2
0	1	1	-1
1	0	0	0
1	0	1	1
1	1	0	-2
1	1	1	-1

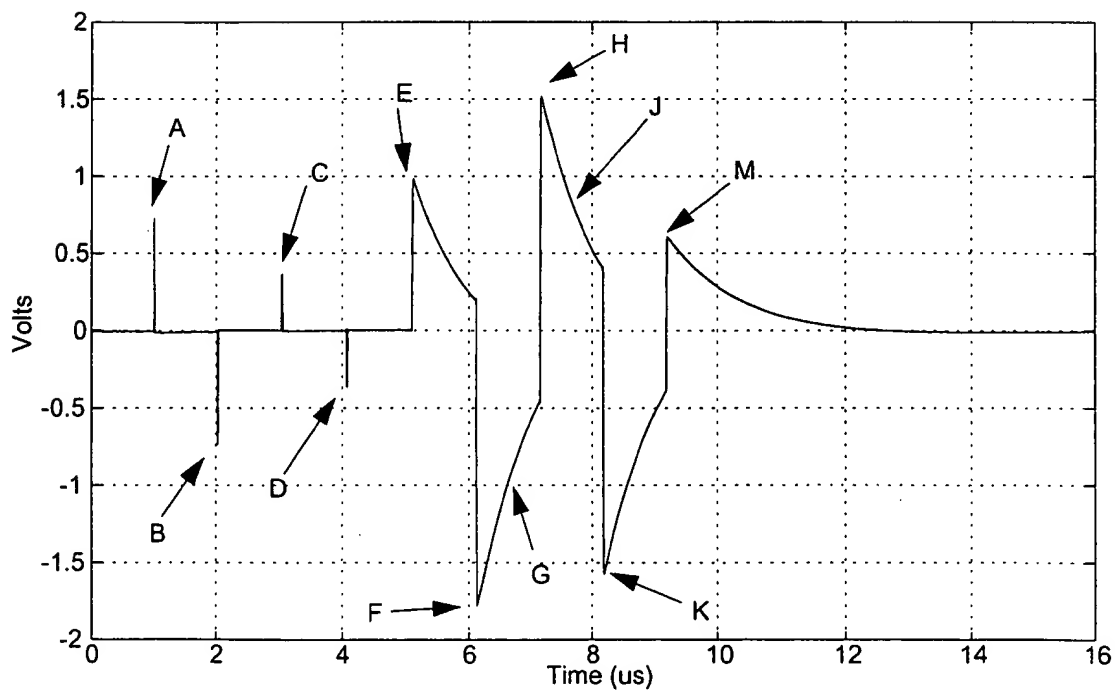


Figure 40–19—Example of transmitter test mode 1 waveform (1 cycle)

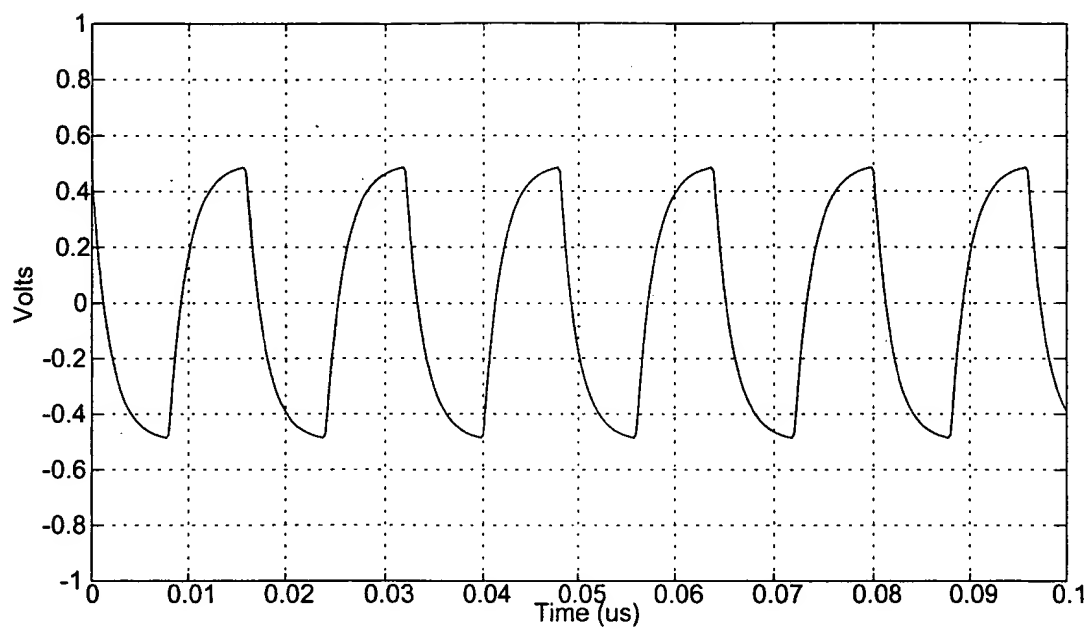


Figure 40-20—Example of transmitter test modes 2 and 3 waveform

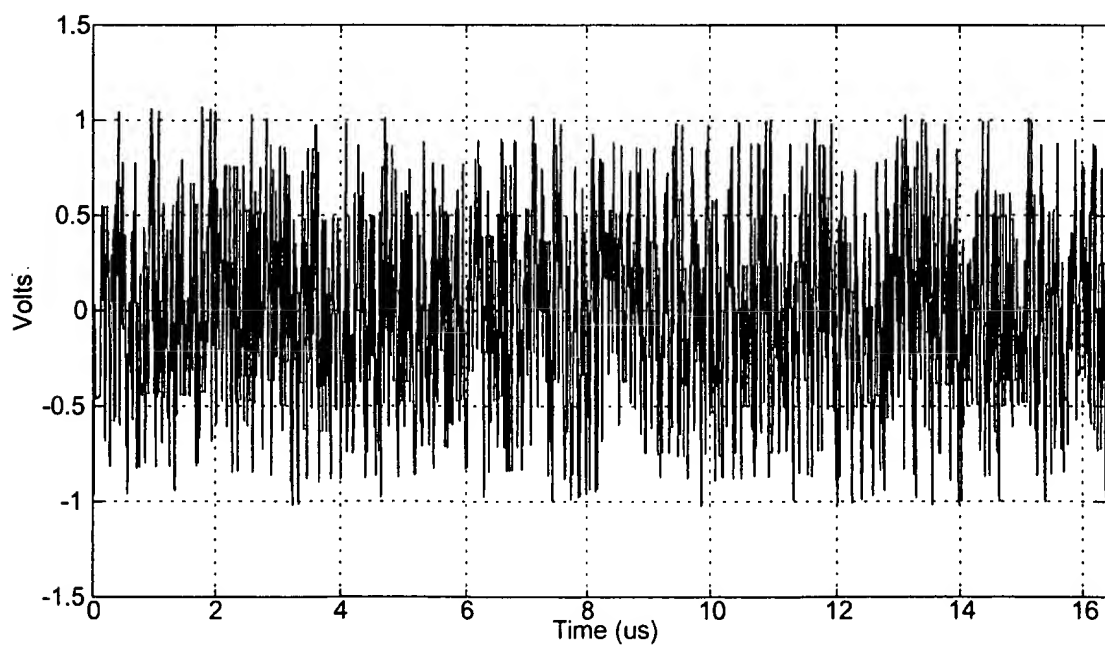


Figure 40-21—Example of Transmitter Test Mode 4 waveform (1 cycle)



### 40.6.1.1.3 Test Fixtures

The following fixtures (illustrated by Figure 40–22, Figure 40–23, Figure 40–24, and Figure 40–25), or their functional equivalents, shall be used for measuring the transmitter specifications described in 40.6.1.2.

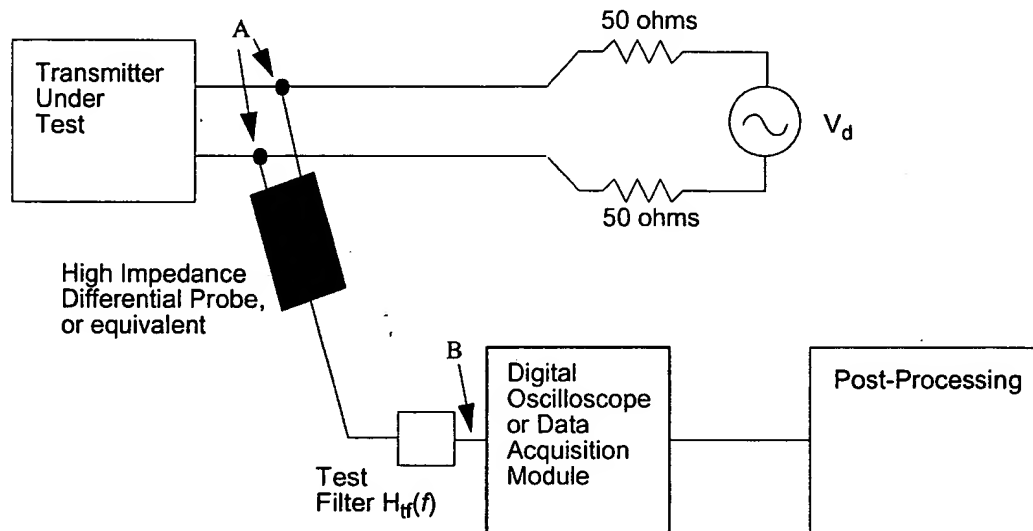


Figure 40–22—Transmitter test fixture 1 for template measurement

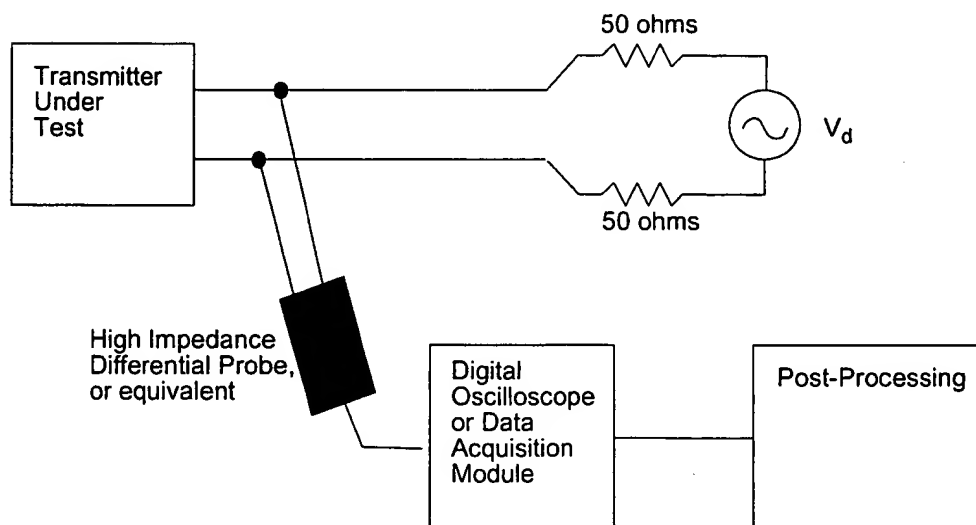


Figure 40–23—Transmitter test fixture 2 for droop measurement

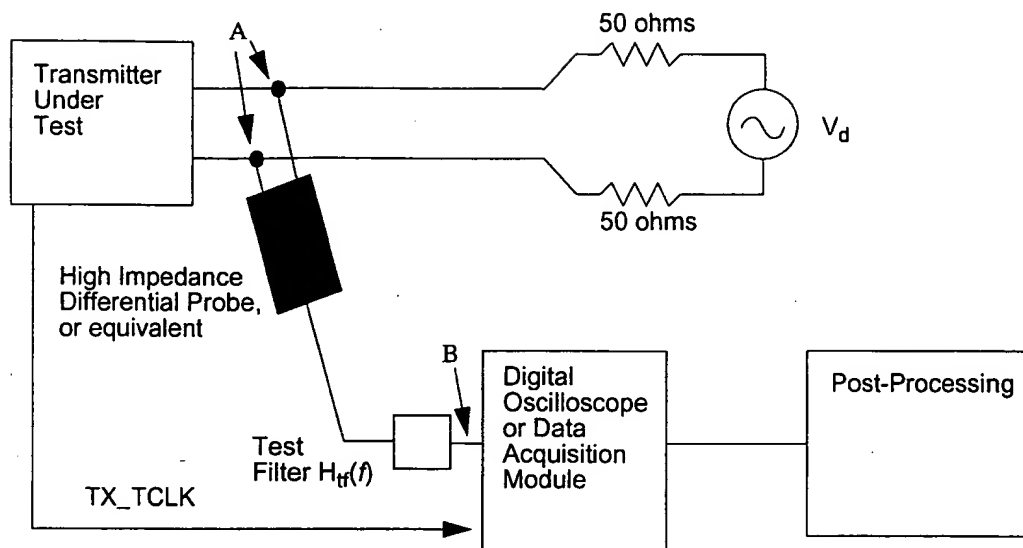


Figure 40-24—Transmitter test fixture 3 for distortion measurement

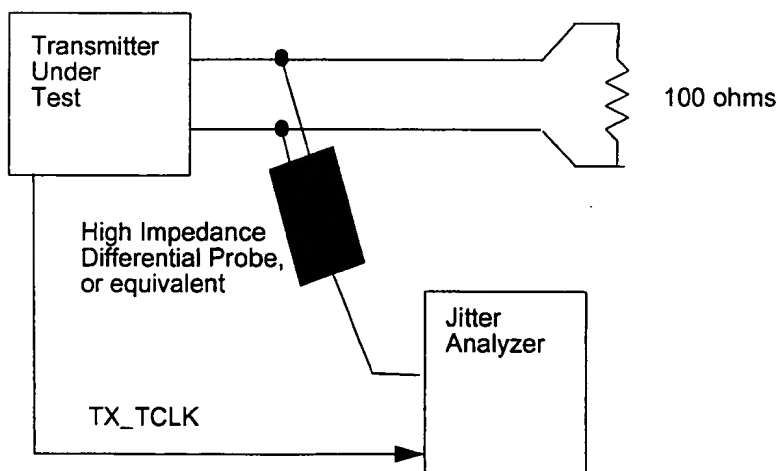


Figure 40-25—Transmitter test fixture 4 for transmitter jitter measurement

The test filter,  $H_{tf}(f)$ , used in transmitter test fixtures 1 and 3 may be located between the points A and B as long as the test filter does not significantly alter the impedance seen by the transmitter. The test filter may instead be implemented as a digital filter in the post processing block. The test filter shall have the following continuous time transfer function or its discrete time equivalent:

$$H_{tf}(f) = \frac{jf}{jf + 2 \times 10^6} \quad f \text{ in Hz}$$

NOTE— $j$  denotes the square root of  $-1$ .

The disturbing signal,  $V_d$ , shall have the characteristics listed in Table 40–9.

**Table 40–9— $V_d$  Characteristics**

Characteristic	Transmit test fixture 1	Transmit test fixture 2	Transmit test fixture 3
Waveform	Sine wave		
Amplitude	2.8 volts peak-to-peak	2.8 volts peak-to-peak	5.4 volts peak-to-peak
Frequency	31.25 MHz	31.25 MHz	20.833 MHz (125/6 MHz)
Purity	All harmonics >40 dB below fundamental		

The post-processing block has two roles. The first is to remove the disturbing signal from the measurement. A method of removing the disturbing signal is to take a single shot acquisition of the transmitted signal plus test pattern, then remove the best fit of a sine wave at the fundamental frequency of the disturbing signal from the measurement. It will be necessary to allow the fitting algorithm to adjust the frequency, phase, and amplitude parameters of the sine wave to achieve the best fit.

The second role of the post-processing block is to compare the measured data with the templates, droop specification, or distortion specification.

Trigger averaging of the transmitter output to remove measurement noise and increase measurement resolution is acceptable provided it is done in a manner that does not average out possible distortions caused by the interaction of the transmitter and the disturbing voltage. For transmitter template and droop measurements, averaging can be done by ensuring the disturbing signal is exactly synchronous to the test pattern so that the phase of the disturbing signal at any particular point in the test pattern remains constant. Trigger averaging also requires a triggering event that is synchronous to the test pattern. A trigger pulse generated by the PHY would be ideal for this purpose; however, in practice, triggering off the waveform generated by one of the other transmitter outputs that does not have the disturbing signal present may be possible.

NOTE—The disturbing signal may be made synchronous to the test pattern by creating the disturbing signal using a source of the transmit clock for the PHY under test, dividing it down to the proper frequency for the disturbing signal, passing the result through a high Q bandpass filter to eliminate harmonics and then amplifying the result to the proper amplitude.

The generator of the disturbing signal must have sufficient linearity and range so it does not introduce any appreciable distortion when connected to the transmitter output (see Table 40–9). This may be verified by replacing the transmitter under test with another identical disturbing signal generator having a different frequency output and verifying that the resulting waveform's spectrum does not show significant distortion products.

Additionally, to allow for measurement of transmitted jitter in master and slave modes, the PHY shall provide access to the 125 MHz symbol clock, TX\_TCLK, that times the transmitted symbols (see 40.4.2.2). The PHY shall provide a means to enable this clock output if it is not normally enabled.

#### 40.6.1.2 Transmitter electrical specifications

The PMA shall provide the Transmit function specified in 40.4.2.2 in accordance with the electrical specifications of this clause.

Where a load is not specified, the transmitter shall meet the requirements of this clause with a 100  $\Omega$  resistive differential load connected to each transmitter output.

The tolerance on the poles of the test filters used in this subclause shall be  $\pm 1\%$ .

Practical considerations prevent measurement of the local transmitter performance in the presence of the remotely driven signal in this standard; however, the design of the transmitter to tolerate the presence of the remotely driven signal with acceptable distortion or other changes in performance is a critical issue and must be addressed by the implementor. To this end, a disturbing sine wave is used to simulate the presence of a remote transmitter for a number of the transmitter tests described in the following subordinate subclauses.

##### 40.6.1.2.1 Peak differential output voltage and level accuracy

The absolute value of the peak of the waveform at points A and B, as defined in Figure 40–19, shall fall within the range of 0.67 V to 0.82 V (0.75 V  $\pm$  0.83 dB). These measurements are to be made for each pair while operating in test mode 1 and observing the differential signal output at the MDI using transmitter test fixture 1 with no intervening cable.

The absolute value of the peak of the waveforms at points A and B shall differ by less than 1%.

The absolute value of the peak of the waveform at points C and D as defined in Figure 40–19 shall differ by less than 2% from 0.5 times the average of the absolute values of the peaks of the waveform at points A and B.

##### 40.6.1.2.2 Maximum output droop

The magnitude of the negative peak value of the waveform at point G, as defined in Figure 40–19, shall be greater than 73.1% of the magnitude of the negative peak value of the waveform at point F. These measurements are to be made for each pair while in test mode 1 and observing the differential signal output at the MDI using transmit test fixture 2 with no intervening cable. Point G is defined as the point exactly 500 ns after point F. Point F is defined as the point where the waveform reaches its minimum value at the location indicated in Figure 40–19. Additionally, the magnitude of the peak value of the waveform at point J as defined in Figure 40–19 shall be greater than 73.1% of the magnitude of the peak value of the waveform at point H. Point J is defined as the point exactly 500 ns after point H. Point H is defined as the point where the waveform reaches its maximum value at the location indicated in Figure 40–19.

##### 40.6.1.2.3 Differential output templates

The voltage waveforms around points A, B, C, D defined in Figure 40–19, after the normalization described herein, shall lie within the time domain template 1 defined in Figure 40–26 and the piecewise linear interpolation between the points in Table 40–10. These measurements are to be made for each pair while in test mode 1 and while observing the differential signal output at the MDI using transmitter test fixture 1 with no intervening cable. The waveforms may be shifted in time as appropriate to fit within the template.

The waveform around point A is normalized by dividing by the peak value of the waveform at A.

The waveform around point B is normalized by dividing by the negative of the peak value of the waveform at A.

The waveform around point C is normalized by dividing by 1/2 the peak value of the waveform at A.

The waveform around point D is normalized by dividing by the negative of 1/2 the peak value of the waveform at A.

The voltage waveforms around points F and H defined in Figure 40–19, after the normalization described herein, shall lie within the time domain template 2 defined in Figure 40–26 and the piecewise linear interpolation between the points in Table 40–11. These measurements are to be made for each pair while in test mode 1 and while observing the differential signal output at the MDI using transmitter test fixture 1 with no intervening cable. The waveforms may be shifted in time as appropriate to fit within the template.

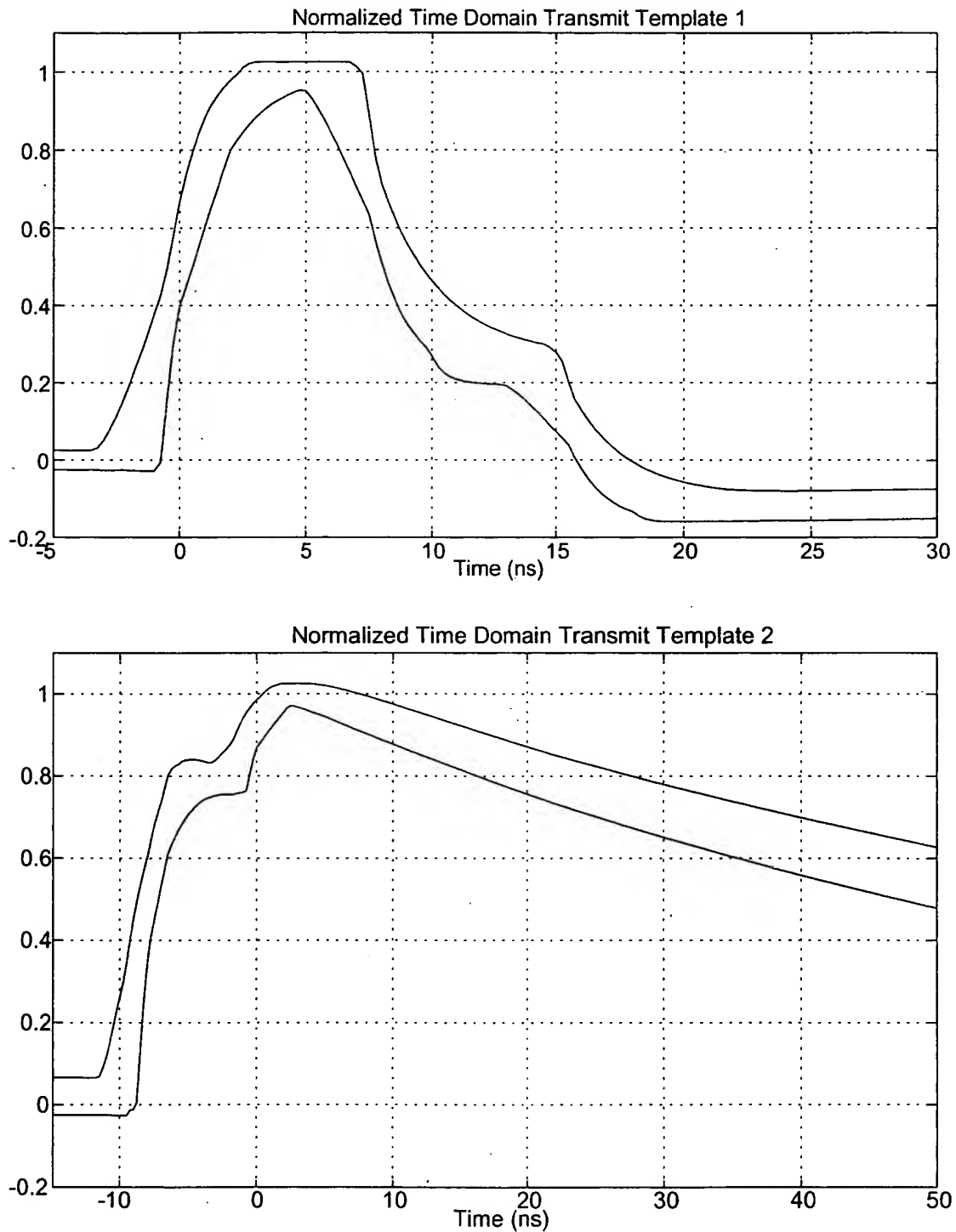
The waveform around point F is normalized by dividing by the peak value of the waveform at F.

The waveform around point H is normalized by dividing by the peak value of the waveform at H.

NOTE—The templates were created with the following assumptions about the elements in the transmit path:

- 1) Digital Filter:  $0.75 + 0.25 z^{-1}$
- 2) Ideal DAC
- 3) Single pole continuous time low pass filter with pole varying from 70.8 MHz to 117 MHz or linear rise/fall time of 5 ns.
- 4) Single pole continuous time high-pass filter (transformer high pass) with pole varying from 1 Hz to 100 kHz.
- 5) Single pole continuous time high-pass filter (test filter) with pole varying from 1.8 MHz to 2.2 MHz.
- 6) Additionally, +0.025 was added to the upper template and –0.025 was added to the lower template to allow for noise and measurement error.

NOTE—The transmit templates are not intended to address electromagnetic radiation limits.



**Figure 40–26—Normalized transmit templates as measured at MDI using transmit test fixture 1**

NOTE—The ASCII for Tables 40–10 and 40–11 is available from <http://www.ieee802.org/3/publication/index.html>.<sup>9</sup>

**Table 40–10—Normalized time domain voltage template 1**

Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit	Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit
–5.00	0.025	–0.026	12.75	0.332	0.195
–4.75	0.025	–0.026	13.00	0.326	0.192
–4.50	0.025	–0.026	13.25	0.320	0.181
–4.25	0.025	–0.026	13.50	0.315	0.169
–4.00	0.025	–0.026	13.75	0.311	0.155
–3.75	0.025	–0.026	14.00	0.307	0.140
–3.50	0.025	–0.026	14.25	0.303	0.124
–3.25	0.031	–0.026	14.50	0.300	0.108
–3.00	0.050	–0.026	14.75	0.292	0.091
–2.75	0.077	–0.026	15.00	0.278	0.074
–2.50	0.110	–0.026	15.25	0.254	0.056
–2.25	0.148	–0.026	15.50	0.200	0.039
–2.00	0.190	–0.027	15.75	0.157	0.006
–1.75	0.235	–0.027	16.00	0.128	–0.023
–1.50	0.281	–0.028	16.25	0.104	–0.048
–1.25	0.329	–0.028	16.50	0.083	–0.068
–1.00	0.378	–0.028	16.75	0.064	–0.084
–0.75	0.427	–0.006	17.00	0.047	–0.098
–0.50	0.496	0.152	17.25	0.032	–0.110
–0.25	0.584	0.304	17.50	0.019	–0.119
0.00	0.669	0.398	17.75	0.007	–0.127
0.25	0.739	0.448	18.00	–0.004	–0.133
0.50	0.796	0.499	18.25	–0.014	–0.145
0.75	0.844	0.550	18.50	–0.022	–0.152
1.00	0.882	0.601	18.75	–0.030	–0.156
1.25	0.914	0.651	19.00	–0.037	–0.158
1.50	0.940	0.701	19.25	–0.043	–0.159

<sup>9</sup>Copyright release for 802.3® template data: Users of this standard may freely reproduce the template data in this subclause so it can be used for its intended purpose.

**Table 40–10—Normalized time domain voltage template 1 (continued)**

Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit	Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit
1.75	0.960	0.751	19.50	–0.048	–0.159
2.00	0.977	0.797	19.75	–0.053	–0.159
2.25	0.992	0.822	20.00	–0.057	–0.159
2.50	1.010	0.845	20.25	–0.061	–0.159
2.75	1.020	0.864	20.50	–0.064	–0.159
3.00	1.024	0.881	20.75	–0.067	–0.159
3.25	1.025	0.896	21.00	–0.070	–0.159
3.50	1.025	0.909	21.25	–0.072	–0.159
3.75	1.025	0.921	21.50	–0.074	–0.158
4.00	1.025	0.931	21.75	–0.076	–0.158
4.25	1.025	0.939	22.00	–0.077	–0.158
4.50	1.025	0.946	22.25	–0.078	–0.158
4.75	1.025	0.953	22.50	–0.079	–0.158
5.00	1.025	0.951	22.75	–0.079	–0.157
5.25	1.025	0.931	23.00	–0.079	–0.157
5.50	1.025	0.905	23.25	–0.080	–0.157
5.75	1.025	0.877	23.50	–0.080	–0.157
6.00	1.025	0.846	23.75	–0.080	–0.156
6.25	1.025	0.813	24.00	–0.080	–0.156
6.50	1.025	0.779	24.25	–0.080	–0.156
6.75	1.025	0.743	24.50	–0.080	–0.156
7.00	1.014	0.707	24.75	–0.080	–0.156
7.25	0.996	0.671	25.00	–0.080	–0.156
7.50	0.888	0.634	25.25	–0.080	–0.156
7.75	0.784	0.570	25.50	–0.080	–0.156
8.00	0.714	0.510	25.75	–0.079	–0.156
8.25	0.669	0.460	26.00	–0.079	–0.156
8.50	0.629	0.418	26.25	–0.079	–0.156
8.75	0.593	0.383	26.50	–0.079	–0.155



**Table 40–10—Normalized time domain voltage template 1 (continued)**

Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit	Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit
9.00	0.561	0.354	26.75	–0.079	–0.155
9.25	0.533	0.330	27.00	–0.078	–0.155
9.50	0.507	0.309	27.25	–0.078	–0.155
9.75	0.483	0.292	27.50	–0.078	–0.154
10.00	0.462	0.268	27.75	–0.078	–0.154
10.25	0.443	0.239	28.00	–0.077	–0.154
10.50	0.427	0.223	28.25	–0.077	–0.153
10.75	0.411	0.213	28.50	–0.077	–0.153
11.00	0.398	0.208	28.75	–0.076	–0.153
11.25	0.385	0.204	29.00	–0.076	–0.152
11.50	0.374	0.201	29.25	–0.076	–0.152
11.75	0.364	0.199	29.50	–0.076	–0.152
12.00	0.355	0.198	29.75	–0.075	–0.151
12.25	0.346	0.197	30.00	–0.075	–0.151
12.50	0.339	0.196			

**Table 40–11—Normalized time domain voltage template 2**

Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit	Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit
–15.00	0.066	–0.025	18.00	0.891	0.779
–14.50	0.066	–0.025	18.50	0.886	0.773
–14.00	0.066	–0.025	19.00	0.881	0.767
–13.50	0.066	–0.025	19.50	0.876	0.762
–13.00	0.066	–0.025	20.00	0.871	0.756
–12.50	0.066	–0.025	20.50	0.866	0.750
–12.00	0.066	–0.025	21.00	0.861	0.745
–11.50	0.069	–0.025	21.50	0.856	0.739
–11.00	0.116	–0.025	22.00	0.852	0.734
–10.50	0.183	–0.025	22.50	0.847	0.728

**Table 40–11—Normalized time domain voltage template 2 (continued)**

Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit	Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit
–10.00	0.261	–0.027	23.00	0.842	0.723
–9.50	0.348	–0.027	23.50	0.838	0.717
–9.00	0.452	–0.013	24.00	0.833	0.712
–8.50	0.535	0.130	24.50	0.828	0.707
–8.00	0.604	0.347	25.00	0.824	0.701
–7.50	0.683	0.451	25.50	0.819	0.696
–7.00	0.737	0.531	26.00	0.815	0.691
–6.50	0.802	0.610	26.50	0.811	0.686
–6.00	0.825	0.651	27.00	0.806	0.680
–5.50	0.836	0.683	27.50	0.802	0.675
–5.00	0.839	0.707	28.00	0.797	0.670
–4.50	0.839	0.725	28.50	0.793	0.665
–4.00	0.837	0.739	29.00	0.789	0.660
–3.50	0.832	0.747	29.50	0.784	0.655
–3.00	0.839	0.752	30.00	0.780	0.650
–2.50	0.856	0.755	30.50	0.776	0.645
–2.00	0.875	0.755	31.00	0.772	0.641
–1.50	0.907	0.758	31.50	0.767	0.636
–1.00	0.941	0.760	32.00	0.763	0.631
–0.50	0.966	0.803	32.50	0.759	0.626
0.00	0.986	0.869	33.00	0.755	0.621
0.50	1.001	0.890	33.50	0.751	0.617
1.00	1.014	0.912	34.00	0.747	0.612
1.50	1.022	0.933	34.50	0.743	0.607
2.00	1.025	0.954	35.00	0.739	0.603
2.50	1.025	0.970	35.50	0.734	0.598
3.00	1.025	0.967	36.00	0.730	0.594
3.50	1.025	0.962	36.50	0.727	0.589
4.00	1.025	0.956	37.00	0.723	0.585

**Table 40–11—Normalized time domain voltage template 2 (continued)**

Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit	Time, ns	Normalized transmit time domain template, upper limit	Normalized transmit time domain template, lower limit
4.50	1.023	0.950	37.50	0.719	0.580
5.00	1.020	0.944	38.00	0.715	0.576
5.50	1.017	0.937	38.50	0.711	0.571
6.00	1.014	0.931	39.00	0.707	0.567
6.50	1.010	0.924	39.50	0.703	0.563
7.00	1.005	0.917	40.00	0.699	0.558
7.50	1.001	0.910	40.50	0.695	0.554
8.00	0.996	0.903	41.00	0.692	0.550
8.50	0.991	0.897	41.50	0.688	0.546
9.00	0.986	0.890	42.00	0.684	0.541
9.50	0.981	0.884	42.50	0.680	0.537
10.00	0.976	0.877	43.00	0.677	0.533
10.50	0.970	0.871	43.50	0.673	0.529
11.00	0.965	0.864	44.00	0.669	0.525
11.50	0.960	0.858	44.50	0.666	0.521
12.00	0.954	0.852	45.00	0.662	0.517
12.50	0.949	0.845	45.50	0.659	0.513
13.00	0.944	0.839	46.00	0.655	0.509
13.50	0.938	0.833	46.50	0.651	0.505
14.00	0.933	0.827	47.00	0.648	0.501
14.50	0.928	0.820	47.50	0.644	0.497
15.00	0.923	0.814	48.00	0.641	0.493
15.50	0.917	0.808	48.50	0.637	0.490
16.00	0.912	0.802	49.00	0.634	0.486
16.50	0.907	0.796	49.50	0.631	0.482
17.00	0.902	0.791	50.00	0.627	0.478
17.50	0.897	0.785			

#### 40.6.1.2.4 Transmitter distortion

When in test mode 4 and observing the differential signal output at the MDI using transmitter test fixture 3, for each pair, with no intervening cable, the peak distortion as defined below shall be less than 10 mV.

The peak distortion is determined by sampling the differential signal output with the symbol rate TX\_TCLK at an arbitrary phase and processing a block of any 2047 consecutive samples with the MATLAB (see 1.3) code listed below or equivalent. Note that this code assumes that the differential signal has already been filtered by the test filter.

NOTE—The ASCII for the following MATLAB code is available from <http://www.ieee802.org/3/publication/index.html>.<sup>10</sup>

MATLAB code for Distortion Post Processing is as follows:

```
%
% Distortion Specification Post Processing
%

% Initialize Variables
clear
symbolRate=125e6;                                % symbol rate
dataFile=input('Data file name: ','s')

% Generate test pattern symbol sequence

scramblerSequence=ones(1,2047);
for i=12:2047
    scramblerSequence(i)=mod(scramblerSequence(i-11) + scramblerSequence(i-9),2);
end

for i=1:2047
    temp=scramblerSequence(mod(i-1,2047)+1) + ...
        2*mod(scramblerSequence(mod(i-2,2047)+1) + scramblerSequence(mod(i-5,2047)+1),2)
    + ...
        4*mod(scramblerSequence(mod(i-3,2047)+1) + scramblerSequence(mod(i-5,2047)+1),2);
    switch temp
        case 0,
            testPattern(i)=0;
        case 1,
            testPattern(i)=1;
        case 2,
            testPattern(i)=2;
        case 3,
            testPattern(i)=-1;
        case 4,
            testPattern(i)=0;
        case 5,
            testPattern(i)=1;
        case 6,
            testPattern(i)=-2;
        case 7,
            testPattern(i)=-1;
    end
end

% Input data file
fid=fopen(dataFile,'r');
sampledData=fscanf(fid,'%f');
```

<sup>10</sup>Copyright release for MATLAB code: Users of this standard may freely reproduce the MATLAB code in this subclause so it can be used for its intended purpose.

```

fclose(fid);
sampledData=sampledData.';

if (length(sampledData) < 2047)
    error('Must have 2047 consecutive samples for processing');
elseif (length(sampledData) > 2047)
    fprintf(1,'\n Warning - only using first 2047 samples in data file');
    sampledData=sampledData(1:2047);
end

% Fit a sine wave to the data and temporarily remove it to yield processed data

options=foptions;
options(1)=0;
options(2)=1e-8;
options(3)=1e-8;
options(14)=2000;
gradfun=zeros(0);
P=fmins('sinefit',[2.0 0 125/6.],options,gradfun,sampledData,symbolRate);

P

processedData=sampledData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:2046]/symbolRate + P(2)*1e-9*symbolRate));

% LMS Cancellation

numberCoeff=70; % Number of coefficients in canceller
coefficients=zeros(1,numberCoeff);
delayLine=testPattern;

% Align data in delayLine to sampled data pattern
temp=xcorr(processedData,delayLine);
index=find(abs(temp)==max(abs(temp)));
index=mod(mod(length(processedData) - index(1),2047)+numberCoeff-10,2047);
delayLine=[delayLine((end-index):end) delayLine(1:(end-index-1))];

% Compute coefficients that minimize squared error in cyclic block

for i=1:2047
    X(i,:)=delayLine(mod([0:(numberCoeff-1)]+i-1,2047)+1);
end
coefficients=(inv(X.' * X)*(processedData*X).').';

% Cancellation
for i=1:2047
    err(i)=processedData(i) - sum(delayLine(1+mod((i-1):(i+numberCoeff-2),2047)).*coefficients);
end

% Add back temporarily removed sine wave

err=err+P(1)*sin(2*pi*(P(3)*1e6*[0:2046]/symbolRate + P(2)*1e-9*symbolRate));

% Re-fit sine wave and do a final removal

```

```

options=options;
options(1)=0;
options(2)=1e-12;
options(3)=1e-12;
options(14)=10000;
gradfun=zeros(0);
P=fmins('sinefit',[2.0 0 125/6.],options,gradfun,err,symbolRate);

P

processedData=sampledData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:2046]/symbolRate + P(2)*1e-9*symbolRate));

% Compute coefficients that minimize squared error in cyclic block
coefficients=(inv(X.' * X)*(processedData*X).').';

% Cancellation
for i=1:2047
    err(i)=processedData(i) - sum(delayLine(1+mod((i-1):(i+numberCoeff-2),2047)).*coefficients);
end

% SNR Calculation
signal=0.5;
noise=mean(err.^2);

SNR=10*log10(signal./noise);

% Output Peak Distortion
peakDistortion=max(abs(err))

% Function for fitting sine wave
function err=sinefit(parameters,data,symbolRate)
err=sum((data- ...
    parameters(1)*sin(2*pi*(parameters(3)*1e6*[0:(length(data)-1)]/symbolRate + parameters(2)*1e-9*symbolRate)).^2);

```

#### 40.6.1.2.5 Transmitter timing jitter

When in test mode 2 or test mode 3, the peak-to-peak jitter  $J_{\text{txout}}$  of the zero crossings of the differential signal output at the MDI relative to the corresponding edge of TX\_TCLK is measured. The corresponding edge of TX\_TCLK is the edge of the transmit test clock, in polarity and time, that generates the zero-crossing transition being measured.

When in the normal mode of operation as the MASTER, the peak-to-peak value of the MASTER TX\_TCLK jitter relative to an unjittered reference shall be less than 1.4 ns. When the jitter waveform on TX\_TCLK is filtered by a high-pass filter,  $H_{jf1}(f)$ , having the transfer function below, the peak-to-peak value of the resulting filtered timing jitter plus  $J_{\text{txout}}$  shall be less than 0.3 ns.

$$H_{jf1}(f) = \frac{jf}{jf + 5000} \quad f \text{ in Hz}$$

When in the normal mode of operation as the SLAVE, receiving valid signals from a compliant PHY operating as the MASTER using the test channel defined in 40.6.1.1.1, with test channel port A connected to the SLAVE, the peak-to-peak value of the SLAVE TX\_TCLK jitter relative to the MASTER TX\_TCLK shall be less than 1.4 ns after the receiver is properly receiving the data and has set bit 10.13 of the GMII management register set to 1. When the jitter waveform on TX\_TCLK is filtered by a high-pass filter,  $H_{jf2}(f)$ , having

the transfer function below, the peak-to-peak value of the resulting filtered timing jitter plus  $J_{\text{txout}}$  shall be no more than 0.4 ns greater than the simultaneously measured peak-to-peak value of the MASTER jitter filtered by  $H_{\text{jf1}}(f)$ .

$$H_{\text{jf2}}(f) = \frac{jf}{jf + 32000} \quad f \text{ in Hz}$$

NOTE— $j$  denotes the square root of  $-1$ .

For all high-pass filtered jitter measurements, the peak-to-peak value shall be measured over an unbiased sample of at least  $10^5$  clock edges. For all unfiltered jitter measurements, the peak-to-peak value shall be measured over an interval of not less than 100 ms and not more than 1 second.

#### 40.6.1.2.6 Transmit clock frequency

The quinary symbol transmission rate on each pair of the master PHY shall be  $125.00 \text{ MHz} \pm 0.01\%$ .

#### 40.6.1.3 Receiver electrical specifications

The PMA shall provide the Receive function specified in 40.4.2.3 in accordance with the electrical specifications of this clause. The patch cabling and interconnecting hardware used in test configurations shall be within the limits specified in 40.7.

##### 40.6.1.3.1 Receiver differential input signals

Differential signals received at the MDI that were transmitted from a remote transmitter within the specifications of 40.6.1.2 and have passed through a link specified in 40.7 are translated into one of the PMA\_UNITDATA.indicate messages with a 4-D symbol error rate less than  $10^{-10}$  and sent to the PCS after link reset completion. Since the 4-D symbols are not accessible, this specification shall be satisfied by a frame error rate less than  $10^{-7}$  for 125 octet frames.

##### 40.6.1.3.2 Receiver frequency tolerance

The receive feature shall properly receive incoming data with a 5-level symbol rate within the range  $125.00 \text{ MHz} \pm 0.01\%$ .

##### 40.6.1.3.3 Common-mode noise rejection

This specification is provided to limit the sensitivity of the PMA receiver to common-mode noise from the cabling system. Common-mode noise generally results when the cabling system is subjected to electromagnetic fields. Figure 40–27 shows the test configuration, which uses a capacitive cable clamp, that injects common-mode signals into a cabling system.

A 100-meter, 4-pair Category 5 cable that meets the specification of 40.7 is connected between two 1000BASE-T PHYs and inserted into the cable clamp. The cable should be terminated on each end with an MDI connector plug specified in 40.8.1. The clamp should be located a distance of ~20 cm from the receiver. It is recommended that the cable between the transmitter and the cable clamp be installed either in a linear run or wrapped randomly on a cable rack. The cable rack should be at least 3 m from the cable clamp. In addition, the cable clamp and 1000BASE-T receiver should be placed on a common copper ground plane and the ground of the receiver should be in contact with the ground plane. The chassis grounds of all test equipment used should be connected to the copper ground plane. No connection is required between the copper ground plane and an external reference. A description of the cable clamp, as well as the validation procedure, can be found in Annex 40B.

A signal generator with a  $50\ \Omega$  impedance is connected to one end of the clamp and an oscilloscope with a  $50\ \Omega$  input is connected to the other end of the clamp. The signal generator shall be capable of providing a sine wave signal of 1 MHz to 250 MHz. The output of the signal generator is adjusted for a voltage of 1.0 V<sub>rms</sub> (1.414 V<sub>peak</sub>) on the oscilloscope.

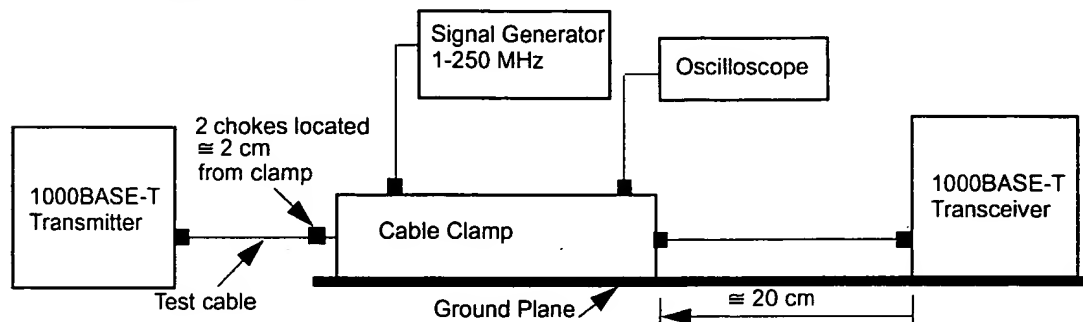


Figure 40-27—Receiver common-mode noise rejection test

While sending data from the transmitter, the receiver shall send the proper PMA\_UNITDATA.indicate messages to the PCS as the signal generator frequency is varied from 1 MHz to 250 MHz.

NOTE—Although the signal specification is constrained within the 1–100 MHz band, this test is performed up to 250 MHz to ensure the receiver under test can tolerate out-of-band (100–250 MHz) noise.

#### 40.6.1.3.4 Alien Crosstalk noise rejection

While receiving data from a transmitter specified in 40.6.1.2 through a link segment specified in 40.7 connected to all MDI duplex channels, a receiver shall send the proper PMA\_UNITDATA.indicate message to the PCS when any one of the four pairs is connected to a noise source as described in Figure 40-28. Because symbol encoding is employed, this specification shall be satisfied by a frame error rate of less than  $10^{-7}$  for 125 octet frames. The level of the noise signal at the MDI is nominally 25 mV peak-to-peak. (Measurements are to be made on each of the four pairs.) The noise source shall be connected to one of the MDI inputs using Category 5 balanced cable of a maximum length of 0.5 m.

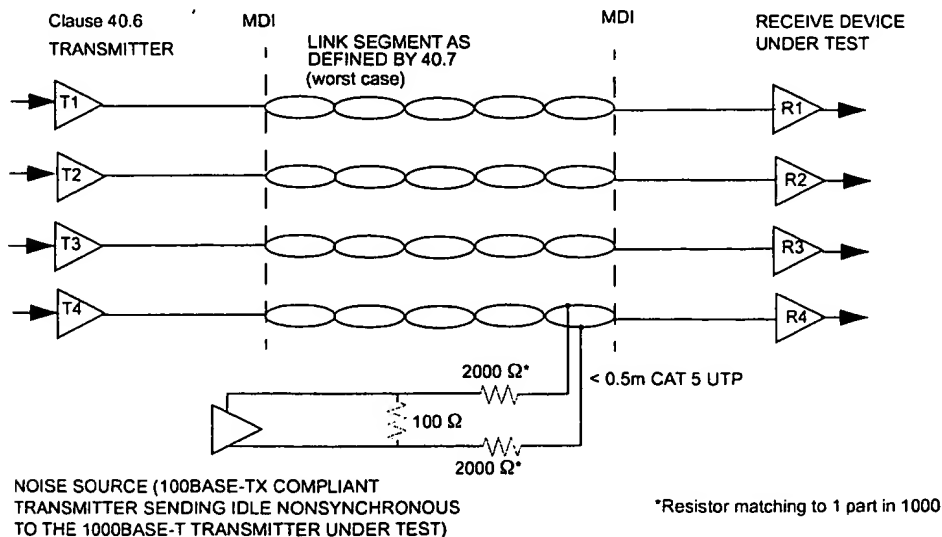


Figure 40-28—Differential mode noise rejection test



## 40.7 Link segment characteristics

1000BASE-T is designed to operate over a 4-pair Category 5 balanced cabling system. Each of the four pairs supports an effective data rate of 250 Mbps in each direction simultaneously. The term “link segment” used in this clause refers to four duplex channels. The term “duplex channel” will be used to refer to a single channel with full duplex capability. Specifications for a link segment apply equally to each of the four duplex channels. All implementations of the balanced cabling link shall be compatible at the MDI.

### 40.7.1 Cabling system characteristics

The cabling system used to support 1000BASE-T requires 4 pairs of Category 5 balanced cabling with a nominal impedance of 100 Ω. The cabling system components (cables, cords, and connectors) used to provide the link segment shall consist of Category 5 components as specified in ANSI/TIA/EIA-568-A:1995 and ISO/IEC 11801:1995. Additionally:

- a) 1000BASE-T uses a star topology with Category 5 balanced cabling used to connect PHY entities.
- b) 1000BASE-T is an ISO/IEC 11801 Class D application, with additional installation requirements and transmission parameters specified in Annex 40A.
- c) The width of the PMD transmit signal spectrum is approximately 80 MHz.
- d) The use of shielding is outside the scope of this standard.

### 40.7.2 Link transmission parameters

The transmission parameters contained in this subclause are specified to ensure that a Category 5 link segment of up to at least 100 m will provide a reliable medium. The transmission parameters of the link segment include insertion loss, delay parameters, characteristic impedance, NEXT loss, ELFEXT loss, and return loss.

Link segment testing shall be conducted using source and load impedances of 100 Ω. The tolerance on the poles of the test filter used in this subclause shall be no worse than 1%.

#### 40.7.2.1 Insertion loss

The insertion loss of each duplex channel shall be less than

$$\text{Insertion\_Loss}(f) < 2.1 f^{0.529} + 0.4/f \quad (\text{dB})$$

at all frequencies from 1 MHz to 100 MHz. This includes the attenuation of the balanced cabling pairs, including work area and equipment cables plus connector losses within each duplex channel. The insertion loss specification shall be met when the duplex channel is terminated in 100 Ω.

NOTE—The above equation approximates the insertion loss specification at discrete frequencies for Category 5 100-meter links specified in ANSI/TIA/EIA-568-A Annex E and in TIA/EIA TSB 67.

#### 40.7.2.2 Differential characteristic impedance

The nominal differential characteristic impedance of each link segment duplex channel, which includes cable cords and connecting hardware, is 100 Ω for all frequencies between 1 MHz and 100 MHz.

#### 40.7.2.3 Return loss

Each link segment duplex channel shall meet or exceed the return loss specified in the following equation at all frequencies from 1 MHz to 100 MHz

$$\text{Return\_Loss}(f) \begin{cases} 15 & (1 - 20 \text{ MHz}) \\ 15 - 10\log_{10}(f/20) & (20 - 100 \text{ MHz}) \end{cases} \text{ (dB)}$$

where  $f$  is the frequency in MHz. The reference impedance shall be 100  $\Omega$ .

### 40.7.3 Coupling parameters

In order to limit the noise coupled into a duplex channel from adjacent duplex channels, Near-End Crosstalk (NEXT) loss and Equal Level Far-End Crosstalk (ELFEXT) loss are specified for each link segment. Each duplex channel can be disturbed by more than one duplex channel. Requirements for Multiple Disturber Near-End Crosstalk (MDNEXT) are satisfied even when worst case conditions of differential pair-to-pair NEXT as specified under 40.7.3.1.1 occur. Therefore, there are no separate requirements for MDNEXT. Requirements for Multiple Disturber Equal-Level Far-End Crosstalk (MDELNEXT) loss are specified in 40.7.3.2.2.

#### 40.7.3.1 Near-End Crosstalk (NEXT)

##### 40.7.3.1.1 Differential Near-End Crosstalk

In order to limit the crosstalk at the near end of a link segment, the differential pair-to-pair Near-End Crosstalk (NEXT) loss between a duplex channel and the other three duplex channels is specified to meet the symbol error rate objective specified in 40.1. The NEXT loss between any two duplex channels of a link segment shall be at least

$$27.1 - 16.8\log_{10}(f/100)$$

where  $f$  is the frequency over the range of 1 MHz to 100 MHz.

NOTE—The above equation approximates the NEXT loss specification at discrete frequencies for Category 5 100-meter links specified in ANSI/TIA/EIA-568-A Annex E and in TSB-67.

#### 40.7.3.2 Far-End Crosstalk (FEXT)

##### 40.7.3.2.1 Equal Level Far-End Crosstalk (ELFEXT) loss

Equal Level Far-End Crosstalk (ELFEXT) loss is specified in order to limit the crosstalk at the far end of each link segment duplex channel and meet the BER objective specified in 40.6.1.3.1. Far-End Crosstalk (FEXT) is crosstalk that appears at the far end of a duplex channel (disturbed channel), which is coupled from another duplex channel (disturbing channel) with the noise source (transmitters) at the near end. FEXT loss is defined as

$$\text{FEXT\_Loss}(f) = 20\log_{10}[V_{pds}(f)/V_{pcn}(f)]$$

and ELFEXT\_Loss is defined as

$$\text{ELFEXT\_Loss}(f) = 20\log_{10}[V_{pds}(f)/V_{pcn}(f)] - \text{SLS\_Loss}(f)$$

where

- $V_{pds}$  is the peak voltage of disturbing signal (near-end transmitter)
- $V_{pcn}$  is the peak crosstalk noise at far end of disturbed channel
- $\text{SLS\_Loss}$  is the insertion loss of disturbed channel in dB

The worst pair ELFEXT loss between any two duplex channels shall be greater than  $17 - 20\log_{10}(f/100)$  dB where  $f$  is the frequency over the range of 1 MHz to 100 MHz.

#### 40.7.3.2.2 Multiple Disturber Equal Level Far-End Crosstalk (MDELTEXT) loss

Since four duplex channels are used to transfer data between PMDs, the FEXT that is coupled into a data carrying channel will be from the three adjacent disturbing duplex channels. This specification is consistent with three channel-to-channel disturbers—one with a ELFEXT loss of at least  $17 - 20\log_{10}(f/100)$  dB, one with a ELFEXT loss of at least  $19.5 - 20\log_{10}(f/100)$  dB, and one with a ELFEXT loss of at least  $23 - 20\log_{10}(f/100)$  dB. To ensure the total FEXT coupled into a duplex channel is limited, multiple disturber ELFEXT loss is specified as the power sum of the individual ELFEXT losses.

The Power Sum loss between a duplex channel and the three adjacent disturbers shall be

$$\text{PSELFEXT loss} > 14.4 - 20\log_{10}(f/100) \text{ dB}$$

where  $f$  is the frequency over the range of 1 MHz to 100 MHz.

#### 40.7.3.2.3 Multiple-Disturber Power Sum Equal Level Far-End Crosstalk (PSELFEXT) loss

PSELFEXT loss is determined by summing the magnitude of the three individual pair-to-pair differential ELFEXT loss values over the frequency range 1 to 100 MHz as follows:

$$\text{PSELFEXT\_Loss}(f) = -10\log_{10} \sum_{i=1}^{i=3} 10^{-(NL(f)i)/10}$$

where

$NL(f)i$  is the magnitude of ELFEXT loss at frequency  $f$  of pair combination  $i$   
 $i$  is the 1, 2, or 3 (pair-to-pair combination)

#### 40.7.4 Delay

In order to simultaneously send data over four duplex channels in parallel, the propagation delay of each duplex channel as well as the difference in delay between any two of the four channels are specified. This ensures the 1000 Mbps data that is divided across four channels can be properly reassembled at the far-end receiver. This also ensures the round-trip delay requirement for effective collision detection is met.

##### 40.7.4.1 Maximum link delay

The propagation delay of a link segment shall not exceed 570 ns at all frequencies between 2 MHz and 100 MHz.

##### 40.7.4.2 Link delay skew

The difference in propagation delay, or skew, between all duplex channel pair combinations of a link segment, under all conditions, shall not exceed 50 ns at all frequencies from 2 MHz to 100 MHz. It is a further functional requirement that, once installed, the skew between any two of the four duplex channels due to environmental conditions shall not vary more than 10 ns within the above requirement.

#### 40.7.5 Noise environment

The 1000BASE-T noise environment consists of noise from many sources. The primary noise sources that impact the objective BER are NEXT and echo interference, which are reduced to a small residual noise using cancelers. The remaining noise sources, which are secondary sources, are discussed in the following list.

The 1000BASE-T noise environment consists of the following:

- a) Echo from the local transmitter on the same duplex channel (cable pair). Echo is caused by the hybrid function used to achieve simultaneous bi-directional transmission of data and by impedance discontinuities in the link segment. It is impractical to achieve the objective BER without using echo cancellation. Since the symbols transmitted by the local disturbing transmitter are available to the cancellation processor, echo interference can be reduced to a small residual noise using echo cancellation methods.
- b) Near-End Crosstalk (NEXT) interference from the local transmitters on the duplex channels (cable pairs) of the link segment. Each receiver will experience NEXT interference from three adjacent transmitters. NEXT cancelers are used to reduce the interference from each of the three disturbing transmitters to a small residual noise. NEXT cancellation is possible since the symbols transmitted by the three disturbing local transmitters are available to the cancellation processor. NEXT cancelers can reduce NEXT interference by at least 20 dB.
- c) Far-End Crosstalk (FEXT) noise at a receiver is from three disturbing transmitters at the far end of the duplex channel (cable pairs) of the link segment. FEXT noise can be cancelled in the same way as echo and NEXT interference although the symbols from the remote transmitters are not immediately available. However, FEXT noise is much smaller than NEXT interference and can generally be tolerated.
- d) Inter-Symbol Interference (ISI) noise. ISI is the extraneous energy from one signaling symbol that interferes with the reception of another symbol on the same channel.
- e) Noise from non-idealities in the duplex channel, transmitters, and receivers; for example, DAC/ADC non-linearity, electrical noise (shot and thermal), and non-linear channel characteristics.
- f) Noise from sources outside the cabling that couple into the link segment via electric and magnetic fields.
- g) Noise from signals in adjacent cables. This noise is referred to as alien NEXT noise and is generally present when cables are bound tightly together. Since the transmitted symbols from the alien NEXT noise source are not available to the cancellation processor (they are in another cable), it is not possible to cancel the alien NEXT noise. To ensure robust operation the alien NEXT noise must meet the specification of 40.7.5.1.

#### 40.7.6 External coupled noise

The noise coupled from external sources that is measured at the output of a filter connected to the output of the near end of a disturbed duplex channel should not exceed 40 mV peak-to-peak. The filter for this measurement is a fifth order Butterworth filter with a 3 dB cutoff at 100MHz.

#### 40.8 MDI specification

This subclause defines the MDI. The link topology requires a crossover function in a DTE-to-DTE connection. See 40.4.4 for a description of the automatic MDI/MDI-X configuration.

##### 40.8.1 MDI connectors

Eight-pin connectors meeting the requirements of subclause 3 and Figures 1 through 4 of IEC 60603-7: 1990 shall be used as the mechanical interface to the balanced cabling. The plug connector shall be used on the balanced cabling and the jack on the PHY. These connectors are depicted (for informational use only) in Figure 40-29 and Figure 40-30. The assignment of PMA signals to connector contacts for PHYs is shown in Table 40-12.

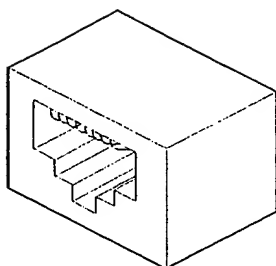


Figure 40-29—MDI connector

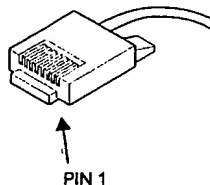


Figure 40-30—Balanced cabling connector

Table 40-12—Assignment of PMA signal to MDI and MDI-X pin-outs

Contact	MDI	MDI-X
1	BI_DA+	BI_DB+
2	BI_DA–	BI_DB–
3	BI_DB+	BI_DA+
4	BI_DC+	BI_DD+
5	BI_DC–	BI_DD–
6	BI_DB–	BI_DA–
7	BI_DD+	BI_DC+
8	BI_DD–	BI_DC–

#### 40.8.2 Crossover function

Although the automatic MDI/MDI-X configuration (see 40.4.4) is not required for successful operation of 1000BASE-T, it is a functional requirement that a crossover function be implemented in every link segment to support the operation of Auto-Negotiation. The crossover function connects the transmitters of one PHY to the receivers of the PHY at the other end of the link segment. Crossover functions may be implemented internally to a PHY or else-where in the link segment. For a PHY that does not implement the crossover function, the MDI labels in the middle column of Table 40-12 refer to its own internal circuits. For PHYs that do implement the internal crossover, the MDI labels in the last column of Table 40-12 refer to the internal circuits of the remote PHY of the link segment. Additionally, the MDI connector for a PHY that implements the crossover function shall be marked with the graphical symbol X. The crossover function specified here is not compatible with the crossover function specified in 14.5.2 for pairs TD and RD.

When a link segment connects a single-port device to a multiport device, it is recommended that the crossover be implemented in the PHY local to the multiport device. If neither or both PHYs of a link segment contain internal crossover functions, an additional external crossover is necessary. It is recommended that the crossover be visible to an installer from one of the PHYs. When both PHYs contain internal crossovers,

it is further recommended that, in networks in which the topology identifies either a central backbone segment or a central device, the PHY furthest from the central element be assigned the external crossover to maintain consistency.

Implicit implementation of the crossover function within a twisted-pair cable or at a wiring panel, while not expressly forbidden, is beyond the scope of this standard.

### 40.8.3 MDI electrical specifications

The MDI connector (jack) when mated with a specified balanced cabling connector (plug) shall meet the electrical requirements for Category 5 connecting hardware for use with 100-ohm Category 5 cable as specified in ANSI/TIA/EIA-568-A:1995 and ISO/IEC 11801:1995.

The mated MDI/balanced cabling connector pair shall have a FEXT loss not less than  $40 - 20\log_{10}(f/100)$  (where  $f$  is the frequency over the range 1 MHz to 100 MHz) between all contact pair combinations shown in Table 40-12.

No spurious signals shall be emitted onto the MDI when the PHY is held in power-down mode (as defined in 22.2.4.1.5) independent of the value of TX\_EN, when released from power-down mode, or when external power is first applied to the PHY.

#### 40.8.3.1 MDI return loss

The differential impedance at the MDI for each transmit/receive channel shall be such that any reflection due to differential signals incident upon the MDI from a balanced cabling having an impedance of  $100 \Omega \pm 15\%$  is attenuated, relative to the incident signal, at least 16 dB over the frequency range of 1.0 MHz to 40 MHz and at least  $10 - 20\log_{10}(f/80)$  dB over the frequency range 40 MHz to 100 MHz ( $f$  in MHz). This return loss shall be maintained at all times when the PHY is transmitting data or control symbols.

#### 40.8.3.2 MDI impedance balance

Impedance balance is a measurement of the impedance-to-ground difference between the two MDI contacts used by a duplex link channel and is referred to as common-mode-to-differential-mode impedance balance. Over the frequency range 1.0 MHz to 100.0 MHz, the common-mode-to-differential-mode impedance balance of each channel of the MDI shall exceed

$$34 - 19.2\log_{10}\left(\frac{f}{50}\right) \text{ dB}$$

where  $f$  is the frequency in MHz when the transmitter is transmitting random or pseudo random data. Test-mode 4 may be used to generate an appropriate transmitter output.

The balance is defined as

$$20\log_{10}\left(\frac{E_{cm}}{E_{dif}}\right)$$

where  $E_{cm}$  is an externally applied sine wave voltage as shown in Figure 40-31 and  $E_{dif}$  is the resulting waveform due only to the applied sine wave and not the transmitted data.

#### NOTES

1—Triggered averaging can be used to separate the component due to the applied common-mode sine wave from the transmitted data component.

2—The imbalance of the test equipment (such as the matching of the test resistors) must be insignificant relative to the balance requirements.

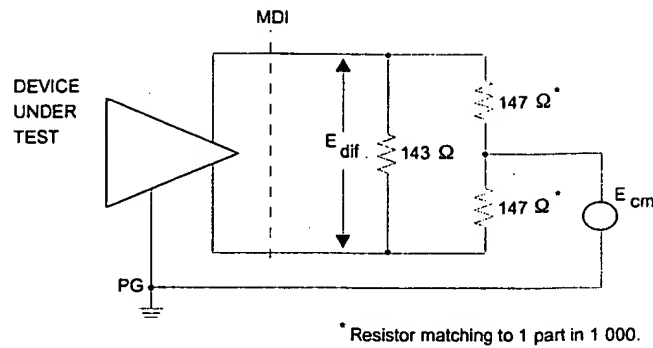


Figure 40-31—MDI impedance balance test circuit

#### 40.8.3.3 MDI common-mode output voltage

The magnitude of the total common-mode output voltage,  $E_{cm\_out}$ , on any transmit circuit, when measured as shown in Figure 40-32, shall be less than 50 mV peak-to-peak when transmitting data.

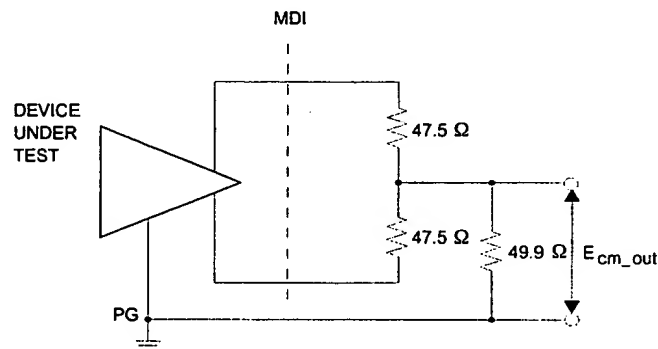


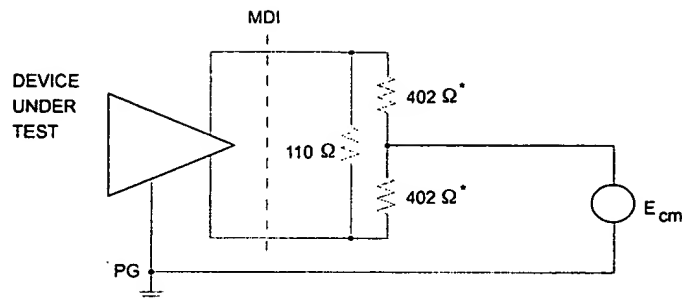
Figure 40-32—Common-mode output voltage test circuit

NOTE—The imbalance of the test equipment (such as the matching of the test resistors) must be insignificant relative to the balance requirements.

#### 40.8.3.4 MDI fault tolerance

Each wire pair of the MDI shall, under all operating conditions, withstand without damage the application of short circuits of any wire to any other wire within the 4-pair cable for an indefinite period of time and shall resume normal operation after the short circuit(s) are removed. The magnitude of the current through such a short circuit shall not exceed 300 mA.

Each wire pair shall withstand without damage a 1000 V common-mode impulse applied at  $E_{cm}$  of either polarity (as indicated in Figure 40-33). The shape of the impulse shall be 0.3/50  $\mu$ s (300 ns virtual front time, 50  $\mu$ s virtual time of half value), as defined in IEC 60060.



\* Resistor matching to 1 part in 100.

**Figure 40-33—MDI fault tolerance test circuit**

## 40.9 Environmental specifications

### 40.9.1 General safety

All equipment meeting this standard shall conform to IEC 60950: 1991.

### 40.9.2 Network safety

This subclause sets forth a number of recommendations and guidelines related to safety concerns; the list is neither complete nor does it address all possible safety issues. The designer is urged to consult the relevant local, national, and international safety regulations to ensure compliance with the appropriate requirements.

LAN cabling systems described in this subclause are subject to at least four direct electrical safety hazards during their installation and use. These hazards are as follows:

- a) Direct contact between LAN components and power, lighting, or communications circuits.
- b) Static charge buildup on LAN cabling and components.
- c) High-energy transients coupled onto the LAN cabling system.
- d) Voltage potential differences between safety grounds to which various LAN components are connected.

Such electrical safety hazards must be avoided or appropriately protected against for proper network installation and performance. In addition to provisions for proper handling of these conditions in an operational system, special measures must be taken to ensure that the intended safety features are not negated during installation of a new network or during modification or maintenance of an existing network.

#### 40.9.2.1 Installation

It is a mandatory requirement that sound installation practice, as defined by applicable local codes and regulations, is followed in every instance in which such practice is applicable.

#### 40.9.2.2 Installation and maintenance guidelines

It is a mandatory requirement that, during installation and maintenance of the cabling plant, care is taken to ensure that non-insulated network cabling conductors do not make electrical contact with unintended conductors or ground.



### 40.9.2.3 Telephony voltages

The use of building wiring brings with it the possibility of wiring errors that may connect telephony voltages to 1000BASE-T equipment. Other than voice signals (which are low voltage), the primary voltages that may be encountered are the “battery” and ringing voltages. Although there is no universal standard, the following maximums generally apply:

Battery voltage to a telephone line is generally 56 Vdc applied to the line through a balanced 400  $\Omega$  source impedance.

Ringing voltage is a composite signal consisting of an ac component and a dc component. The ac component is up to 175 V peak at 20 Hz to 60 Hz with a 100  $\Omega$  source resistance. The dc component is 56 Vdc with a 300  $\Omega$  to 600  $\Omega$  source resistance. Large reactive transients can occur at the start and end of each ring interval.

Although 1000BASE-T equipment is not required to survive such wiring hazards without damage, application of any of the above voltages shall not result in any safety hazard.

NOTE—Wiring errors may impose telephony voltages differentially across 1000BASE-T transmitters or receivers. Because the termination resistance likely to be present across a receiver’s input is of substantially lower impedance than an off-hook telephone instrument, receivers will generally appear to the telephone system as off-hook telephones. Therefore, full-ring voltages will be applied for only short periods. Transmitters that are coupled using transformers will similarly appear like off-hook telephones (though perhaps a bit more slowly) due to the low resistance of the transformer coil.

### 40.9.3 Environment

#### 40.9.3.1 Electromagnetic emission

A system integrating the 1000BASE-T PHY shall comply with applicable local and national codes for the limitation of electromagnetic interference.

#### 40.9.3.2 Temperature and humidity

A system integrating the 1000BASE-T PHY is expected to operate over a reasonable range of environmental conditions related to temperature, humidity, and physical handling (such as shock and vibration). Specific requirements and values for these parameters are considered to be beyond the scope of this standard.

It is recommended that manufacturers indicate in the literature associated with the PHY the operating environmental conditions to facilitate selection, installation, and maintenance.

### 40.10 PHY labeling

It is recommended that each PHY (and supporting documentation) be labeled in a manner visible to the user with at least the following parameters:

- a) Data rate capability in Mb/s
- b) Power level in terms of maximum current drain (for external PHYs)
- c) Port type (i.e., 1000BASE-T)
- d) Any applicable safety warnings

## 40.11 Delay constraints

In half duplex mode, proper operation of a CSMA/CD LAN demands that there be an upper bound on the propagation delays through the network. This implies that MAC, PHY, and repeater implementors must conform to certain delay minima and maxima, and that network planners and administrators conform to constraints regarding the cabling topology and concatenation of devices. MAC constraints are specified in 35.2.4. Topological constraints are contained in Clause 42.

In full duplex mode, predictable operation of the MAC Control PAUSE operation (Clause 31, Annex 31B) also demands that there be an upper bound on the propagation delays through the network. This implies that MAC, MAC Control sublayer, and PHY implementors must conform to certain delay maxima, and that network planners and administrators conform to constraints regarding the cable topology and concatenation of devices.

The reference point for all MDI measurements is the peak point of the mid-cell transition corresponding to the reference code-bit, as measured at the MDI.

### 40.11.1 MDI to GMII delay constraints

Every 1000BASE-T PHY associated with a GMII shall comply with the bit delay constraints specified in Table 40–13 for half duplex operation and Table 40–14 for full duplex operation. These constraints apply for all 1000BASE-T PHYs. For any given implementation, the assertion and de-assertion delays on CRS shall be equal.

**Table 40–13—MDI to GMII delay constraints (half duplex mode)**

Sublayer measurement points	Event	Min (bit times)	Max (bit times)	Input timing reference	Output timing reference
GMII $\leftrightarrow$ MDI	TX_EN Sampled to MDI Output	—	84	GTK_CLK rising	1st symbol of SSD/CSReset/ CSExtend/ CSExtend_Err
	MDI input to CRS assert	—	244	1st symbol of SSD/CSReset	—
	MDI input to CRS de-assert	—	244	1st symbol of SSD/CSReset	—
	MDI input to COL assert	—	244	1st symbol of SSD/CSReset	—
	MDI input to COL de-assert	—	244	1st symbol of SSD/CSReset	—
	TX_EN sampled to CRS assert	—	16	GTK_CLK rising	—
	TX_EN sampled to CRS de-assert	—	16	GTK_CLK rising	—

### 40.11.2 DTE delay constraints (half duplex only)

Every DTE with a 1000BASE-T PHY shall comply with the bit delay constraints specified in Table 40–15 for half duplex operation.

**Table 40–14—MDI to GMII delay constraints (full duplex mode)**

Sublayer measurement points	Event	Min (bit times)	Max (bit times)	Input timing reference	Output timing reference
GMII ↔ MDI	TX_EN Sampled to MDI Output	—	84	GTX_CLK rising	1st symbol of SSD/CSReset/CSExtend/CSExtend_Err
	MDI input to RX_DV de-assert	—	244	1st symbol of CSReset	—

**Table 40–15— DTE delay constraints (half duplex mode)**

Sublayer measurement points	Event	Min (bit times)	Max (bit times)	Input timing reference	Output timing reference
MAC ↔ MDI	MAC transmit start to MDI output	—	132	—	1st symbol of SSD
	MDI input to collision detect	—	292	1st symbol of SSD	—
	MDI input to MDI output (nondeferred or Jam)	—	440	1st symbol of SSD	1st symbol of SSD
	MDI Input to MDI output (worse-case non-deferred transmit)	—	440	1st symbol of SSD	1st symbol of SSD

**40.11.3 Carrier de-assertion/assertion constraint (half duplex mode)**

To ensure fair access to the network, each DTE operating in half duplex mode shall, additionally, satisfy the following: (MAX MDI to MAC Carrier De-assert Detect) – (MIN MDI to MAC Carrier Assert Detect) < 16 Bit Times.

**40.12 Protocol implementation conformance statement (PICS) proforma for Clause 40—Physical coding sublayer (PCS), physical medium attachment (PMA) sublayer and baseband medium, type 1000BASE-T<sup>11</sup>**

The supplier of a protocol implementation that is claimed to conform to this clause shall complete the Protocol Implementation Conformance Statement (PICS) proforma listed in the following subclauses.

Instructions for interpreting and filling out the PICS proforma may be found in Clause 21.

<sup>11</sup> Copyright release for PICS proformas: Users of this standard may freely reproduce the PICS proforma in this subclause so it can be used for its intended purpose and may further publish the completed PICS.

**40.12.1 Identification****40.12.1.1 Implementation identification**

Supplier	
Contact point for queries about the PICS	
Implementation Name(s) and Version(s)	
Other information necessary for full identification—e.g., name(s) and version(s) for machines and/or operating systems; System Name(s)	
<b>NOTES</b> 1—Only the first three items are required for all implementations; other information may be completed as appropriate in meeting the requirements for the identification. 2—The terms Name and Version should be interpreted appropriately to correspond with a supplier's terminology (e.g., Type, Series, Model).	

**40.12.1.2 Protocol summary**

Identification of protocol specification	IEEE Std 802.3-2002®, Clause 40, Physical coding sub-layer (PCS), physical medium attachment (PMA) sub-layer, and baseband medium, type 1000BASE-T
Identification of amendments and corrigenda to this PICS proforma which have been completed as part of this PICS	
Have any Exceptions items been required?      No <input type="checkbox"/> Yes <input type="checkbox"/> (See Clause 21—The answer Yes means that the implementation does not conform to the standard)	
Date of Statement	

**40.12.2 Major capabilities/options**

Item	Feature	Subclause	Status	Support	Value/Comment
*GMII	PHY associated with GMII	40.1	O	Yes <input type="checkbox"/> No <input type="checkbox"/>	
*DTE	DTE with PHY not associated with GMII	40.1	O	Yes <input type="checkbox"/> No <input type="checkbox"/>	
AN	Support for Auto-Negotiation (Clause 28)	40.5.1	M	Yes <input type="checkbox"/>	Required
OMS	Operation as MASTER or SLAVE	40.5.1	M	Yes <input type="checkbox"/>	Required
*FDX	PHY supports full duplex mode	40.1	O	Yes <input type="checkbox"/> No <input type="checkbox"/>	
*HDX	PHY support half duplex mode	40.1	O	Yes <input type="checkbox"/> No <input type="checkbox"/>	
*INS	Installation / cabling	40.7	O	Yes <input type="checkbox"/> No <input type="checkbox"/>	Items marked with INS include installation practices and cabling specifications not applicable to a PHY manufacturer.
*AXO	Auto-Crossover	40.4.4	O	Yes <input type="checkbox"/> No <input type="checkbox"/>	PHY supports auto-crossover

### 40.12.3 Clause conventions

Item	Feature	Subclause	Status	Support	Value/Comment
CCO1	The values of all components in test circuits shall be	40.1.6	M	Yes [ ]	Accurate to within $\pm 1\%$ unless otherwise stated.

### 40.12.4 Physical Coding Sublayer (PCS)

Item	Feature	Subclause	Status	Support	Value/Comment
PCT1	The PCS shall	40.3.1.2	M	Yes [ ]	Implement the Data Transmission Enabling process as depicted in Figure 40–8 including compliance with the associated state variables specified in 40.3.3.
PCT2	PCS Transmit function shall	40.3.1.3	M	Yes [ ]	Conform to the PCS Transmit state diagram in Figure 40–9.
PCT3	PCS Transmit shall	40.4.5.1	M	Yes [ ]	Send code-groups according to the value assumed by the tx_mode variable.
PCT4	If the parameter config provided to the PCS by the PHY Control function via the PMA_CONFIG.indicate message assumes the value MASTER, PCS Transmit shall	40.3.1.3.1	M	Yes [ ]	Employ the transmitter side-stream scrambler generator polynomial specified for use with MASTER in 40.3.1.3.1.
PCT5	If the parameter config provided to the PCS by the PHY Control function via the PMA_CONFIG.indicate message assumes the value SLAVE, PCS Transmit shall	40.3.1.3.1	M	Yes [ ]	Employ the transmitter side-stream scrambler generator polynomial specified for use with SLAVE in 40.3.1.3.1.
PCT6	In no case shall	40.3.1.3.1	M	Yes [ ]	The scrambler state be initialized to all zeros.
PCT7	If $tx\_error_n=1$ when the condition $(tx\_enable_n * tx\_enable_{n-2}) = 1$ , error indication is signaled by means of symbol substitution, wherein the values of $Sd_n[5:0]$ are ignored during mapping and the symbols corresponding to the row denoted as "xmt_err" in Table 40–1 and Table 40–2 shall be used.	40.3.1.3.5	M	Yes [ ]	

Item	Feature	Subclause	Status	Support	Value/Comment
PCT8	If $tx\_error_n=0$ when the variable $csreset_n = 1$ , the convolutional encoder reset condition is normal. This condition is indicated by means of symbol substitution, where the values of $Sd_n[5:0]$ are ignored during mapping and the symbols corresponding to the row denoted as "CSReset" in Table 40-1 and Table 40-2 shall be used.	40.3.1.3.5	M	Yes [ ]	
PCT9	If $tx\_error_n=1$ is asserted when the variable $csreset_n = 1$ , the convolutional encoder reset indicates carrier extension. In this condition, the values of $Sd_n[5:0]$ are ignored during mapping and the symbols corresponding to the row denoted as "CSExtend" in Table 40-1 and Table 40-2 shall be used when $TXD_n = 0x'0F$ , and the row denoted as "CSExtend_Err" in Table 40-1 and Table 40-2 shall be used when $TXD_n \neq 0x'0F$ .	40.3.1.3.5	M	Yes [ ]	
PCT10	In case carrier extension with error is indicated during the first octet of CSReset, the error condition shall be encoded during the second octet of CSReset, and during the subsequent two octets of the End-of-Stream delimiter.	40.3.1.3.5	M	Yes [ ]	
PCT11	The symbols corresponding to the SSD1 row in Table 40-1 shall be used when the condition $(tx\_enable_n)^* (!tx\_enable_{n-1}) = 1$ .	40.3.1.3.5	M	Yes [ ]	
PCT12	The symbols corresponding to the SSD2 row in Table 40-1 shall be used when the condition $(tx\_enable_{n-1})^* (!tx\_enable_{n-2}) = 1$ .	40.3.1.3.5	M	Yes [ ]	
PCT13	If carrier extend error is indicated during ESD, the symbols corresponding to the ESD_Ext_Err row in Table 40-1 shall be used.	40.3.1.3.5	M	Yes [ ]	
PCT14	The symbols corresponding to the ESD1 row in Table 40-1 shall be used when the condition $(!tx\_enable_{n-2})^* (tx\_enable_{n-3}) = 1$ , in the absence of carrier extend error indication at time n.	40.3.1.3.5	M	Yes [ ]	

Item	Feature	Subclause	Status	Support	Value/Comment
PCT15	The symbols corresponding to the ESD2_Ext_0 row in shall be used when the condition $(!tx\_enable_{n-3}) * (tx\_enable_{n-4}) * (!tx\_error_n) * (!tx\_error_{n-1}) = 1$ .	40.3.1.3.5	M	Yes [ ]	
PCT16	The symbols corresponding to the ESD2_Ext_1 row in Table 40–1 shall be used when the condition $(!tx\_enable_{n-3}) * (tx\_enable_{n-4}) * (!tx\_error_n) * (tx\_error_{n-1}) * (tx\_error_{n-2}) * (tx\_error_{n-3}) = 1$ .	40.3.1.3.5	M	Yes [ ]	
PCT17	The symbols corresponding to the ESD2_Ext_2 row in Table 40–1 shall be used when the condition $(!tx\_enable_{n-3}) * (tx\_enable_{n-4}) * (tx\_error_n) * (tx\_error_{n-1}) * (tx\_error_{n-2}) * (tx\_error_{n-3}) * (TXD_n=0x0F) = 1$ , in the absence of carrier extend error indication.	40.3.1.3.5	M	Yes [ ]	

#### 40.12.4.1 PCS receive functions

Item	Feature	Subclause	Status	Support	Value/Comment
PCR1	PCS Receive function shall	40.3.1.4	M	Yes [ ]	Conform to the PCS Receive state diagram shown in Figure 40–10a including compliance with the associated state variables as specified in 40.3.3.
PCR2	The PHY shall	40.3.1.4.2	M	Yes [ ]	Descramble the data stream and return the proper sequence of data bits RXD<7:0> to the GMII.
PCR3	For side-stream descrambling, the MASTER PHY shall employ	40.3.1.4.2	M	Yes [ ]	The receiver scrambler generator polynomial specified for MASTER operation in 40.3.1.4.2.
PCR4	For side-stream descrambling, the SLAVE PHY shall employ	40.3.1.4.2	M	Yes [ ]	The receiver scrambler generator polynomial specified for SLAVE operation in 40.3.1.4.2.

**40.12.4.2 Other PCS functions**

Item	Feature	Subclause	Status	Support	Value/Comment
PCO1	The PCS Reset function shall	40.3.1.1	M	Yes [ ]	Be executed any time “power on” or receipt of a request for reset from the management entity occurs, including compliance with the associated state variables as specified in 40.3.3.
PCO2	The PCS shall	40.3.1.5	M	Yes [ ]	Implement the Carrier Sense process as depicted in Figure 40-11, including compliance with the associated state variables as specified in 40.3.3.
PCO3	Symb-timer shall be generated	40.3.3.3	M	Yes [ ]	Synchronously with TX_TCLK.

**40.12.5 Physical Medium Attachment (PMA)**

Item	Feature	Subclause	Status	Support	Value/Comment
PMF1	PMA Reset function shall be executed	40.4.2.1	M	Yes [ ]	At power on and upon receipt of a reset request from the management entity or from PHY Control.
PMF2	PMA Transmit shall	40.4.2.2	M	Yes [ ]	Continuously transmit onto the MDI pulses modulated by the quinary symbols given by tx_symb_vector[B1_DA], tx_symb_vector[B1_DB], tx_symb_vector[B1_DC], and tx_symb_vector[B1_DD], respectively.
PMF3	The four transmitters shall be driven by the same transmit clock, TX_TCLK	40.4.2.2	M	Yes [ ]	
PMF4	PMA Transmit shall	40.4.2.2	M	Yes [ ]	Follow the mathematical description given in 40.4.3.1.
PMF5	PMA Transmit shall comply with	40.4.2.2	M	Yes [ ]	The electrical specifications given in 40.6.
PMF6	When the PMA_CONFIG.indicate parameter config is MASTER, the PMA Transmit function shall	40.4.2.2	M	Yes [ ]	Source the transmit clock TX_TCLK from a local clock source while meeting the transmit jitter requirements of 40.6.1.2.5.



Item	Feature	Subclause	Status	Support	Value/Comment
PMF7	When the PMA_CONFIG.indicate parameter config is SLAVE, the PMA Transmit function shall	40.4.2.2	M	Yes [ ]	Source the transmit clock TX_TCLK from the recovered clock of 40.4.2.5 while meeting the jitter requirements of 40.6.1.2.5.
PMF8	PMA Receive function shall	40.4.2.3	M	Yes [ ]	Translate the signals received on pairs BI_DA BI_DB, BI_DC and BI_DD into the PMA_UNITDATA.indicate parameter rx_symb_vector with a symbol error rate of less than one part in $10^{10}$ .
PMF9	PHY Control function shall	40.4.2.4	M	Yes [ ]	Comply with the state diagram descriptions given in Figure 40-15.
PMF10	The Link Monitor function shall	40.4.2.5	M	Yes [ ]	Comply with the state diagram shown in Figure 40-16.
PMF11	Clock Recovery function shall provide	40.4.2.6	M	Yes [ ]	Provide clocks suitable for signal sampling on each line so that the symbol-error rate indicated in 40.4.2.3 is achieved.
PMF12	The symbol response shall comply with	40.4.3.1	M	Yes [ ]	The electrical specifications given in 40.6.
PMF13	The four signals received on pairs BI_DA, BI_DB, BI_DC, and BI_DD shall be processed within the PMA Receive function to yield	40.4.3.2	M	Yes [ ]	The quinary received symbols rx_symb_vector[BI_DA], rx_symb_vector[BI_DB], rx_symb_vector[BI_DC], and rx_symb_vector[BI_DD].
PMF14	If an automatic configuration method is used, it shall	40.4.4	M	Yes [ ]	Comply with the specifications of 40.4.4.
PMF15	The PMA shall	40.4.5.1	M	Yes [ ]	Generate the config variable continuously and pass it to the PCS via the PMA_CONFIG.indicate primitive.
PMF16	The variable link_det shall take the value	40.4.5.1	AXO:M	N/A [ ] Yes [ ]	TRUE or FALSE as per 40.4.4.1.
PMF17	The variable MDI_status shall take the value	40.4.5.1	AXO:M	N/A [ ] Yes [ ]	MDI or MDI-X as per Table 40-12.
PMF18	PCS Transmit shall	40.4.5.1	M	Yes [ ]	Send code-groups according to the value assumed by tx_mode.
PMF19	The A_timer shall have a period of	40.4.5.2	AXO:M	N/A [ ] Yes [ ]	$1.3s \pm 25\%$ .
PMF20	The maxwait_timer timer shall expire	40.4.5.2	M	Yes [ ]	$750 \pm 10$ ms if config = MASTER or $350 \pm 5$ ms if config = SLAVE

Item	Feature	Subclause	Status	Support	Value/Comment
PMF21	The minwait_timer timer shall expire	40.4.5.2	M	Yes [ ]	$1 \pm 0.1 \mu\text{s}$ after being started.
PMF22	The sample_timer shall have a period of	40.4.5.2	AXO:M	N/A [ ] Yes [ ]	$62 \pm 2\text{ms}$ .
PMF23	The stabilize_timer shall expire	40.4.5.2	M	Yes [ ]	$1 \pm 0.1 \mu\text{s}$ after being started.

#### 40.12.6 Management interface

Item	Feature	Subclause	Status	Support	Value/Comment
MF1	All 1000BASE-T PHYs shall provide support for Auto-Negotiation (Clause 28) and shall be capable of operating as MASTER or SLAVE.	40.5.1	M	Yes [ ]	
MF2	A 100BASE-T PHY shall	40.5.1.1	M	Yes [ ]	Use the management register definitions and values specified in Table 40–3.

##### 40.12.6.1 1000BASE-T Specific Auto-Negotiation Requirements

Item	Feature	Subclause	Status	Support	Value/Comment
AN1	1000BASE-T PHYs shall	40.5.1.2	M	Yes [ ]	Exchange one Auto-Negotiation Base Page, a 1000BASE-T formatted Next Page, and two 1000BASE-T unformatted Next Pages in sequence, without interruption, as specified in Table 40–4.
AN2	The MASTER-SLAVE relationship shall be determined during Auto-Negotiation	40.5.2	M	Yes [ ]	Using Table 40–5 with the 1000BASE-T Technology Ability Next Page bit values specified in Table 40–4 and information received from the link partner.
AN3	Successful completion of the MASTER-SLAVE resolution shall	40.5.2	M	Yes [ ]	Be treated as MASTER-SLAVE configuration resolution complete.
AN4	A seed counter shall be provided to	40.5.2	M	Yes [ ]	Track the number of seed attempts.
AN5	At start-up, the seed counter shall be set to	40.5.2	M	Yes [ ]	Zero.
AN6	The seed counter shall be incremented	40.5.2	M	Yes [ ]	Every time a new random seed is sent.

Item	Feature	Subclause	Status	Support	Value/Comment
AN7	When MASTER-SLAVE resolution is complete, the seed counter shall be reset to 0 and bit 10.15 shall be set to logical zero.	40.5.2	M	Yes [ ]	
AN8	Maximum seed attempts before declaring a MASTER_SLAVE configuration Resolution Fault	40.5.2	M	Yes [ ]	Seven.
AN9	During MASTER_SLAVE configuration, the device with the higher seed value shall	40.5.2	M	Yes [ ]	Become the MASTER.
AN10	During MASTER_SLAVE configuration, the device with the lower seed value shall	40.5.2	M	Yes [ ]	Become the SLAVE.
AN11	Both PHYs set in manual mode to be either MASTER or SLAVE shall be treated as	40.5.2	M	Yes [ ]	MASTER-SLAVE resolution fault (failure) condition.
AN12	MASTER-SLAVE resolution fault (failure) condition shall result in	40.5.2	M	Yes [ ]	MASTER-SLAVE Configuration Resolution Fault bit (10.15) to be set to logical one.
AN13	MASTER-SLAVE Configuration resolution fault condition shall be treated as	40.5.2	M	Yes [ ]	MASTER-SLAVE Configuration Resolution complete.
AN14	MASTER-SLAVE Configuration resolution fault condition shall	40.5.2	M	Yes [ ]	Cause link_status_1000BASE-T to be set to FAIL.

**40.12.7 PMA Electrical Specifications**

Item	Feature	Subclause	Status	Support	Value/Comment
PME15	The PHY shall provide electrical isolation between	40.6.1.1	M	Yes [ ]	The port device circuits including frame ground, and all MDI leads.
PME16	PHY-provided electrical separation shall withstand at least one of three electrical strength tests	40.6.1.1	M	Yes [ ]	a) 1500 V rms at 50Hz to 60Hz for 60 s, applied as specified in Section 5.3.2 of IEC 60950:1991. b) 2250 Vdc for 60 s, applied as specified in Section 5.3.2 of IEC 60950: 1991. c) A sequence of ten 2400 V impulses of alternating polarity, applied at intervals of not less than 1 s. The shape of the impulses shall be 1.2/50 $\mu$ s. (1.2 $\mu$ s virtual front time, 50 $\mu$ s virtual time or half value), as defined in IEC 60060.
PME17	There shall be no insulation breakdown as defined in Section 5.3.2 of IEC 60950, during the test.	40.6.1.1	M	Yes [ ]	
PME18	The resistance after the test shall be at least	40.6.1.1	M	Yes [ ]	2 M $\Omega$ , measured at 500 Vdc.
PME19	The transmitter MASTER-SLAVE timing jitter test channel shall	40.6.1.1.1	M	Yes [ ]	Be constructed by combining 100 $\Omega$ and 120 $\Omega$ cable segments that meet or exceed ISO/IEC 11801 Category 5 specifications for each pair as shown in Figure 40–18 with the lengths and additional restrictions on parameters described in Table 40–6.
PME20	The ends of the MASTER-SLAVE timing jitter test channel shall	40.6.1.1.1	M	Yes [ ]	Be connectorized with connectors meeting or exceeding ANSI/TIA/EIA-568-A:1995 or ISO/IEC 11801:1995 Category 5 specifications.
PME21	The return loss of the MASTER-SLAVE timing jitter test channel shall	40.6.1.1.1	M	Yes [ ]	Meet the return loss requirements of 40.7.2.3.
PME22	The return loss of the MASTER-SLAVE timing jitter test channel shall	40.6.1.1.1	M	Yes [ ]	Meet the crosstalk requirements of 40.7.3 on each pair.
PME23	The test modes described in 40.6.1.1.2 shall be provided for testing of the transmitted waveform, transmitter distortion and transmitted jitter.	40.6.1.1.2	M	Yes [ ]	

Item	Feature	Subclause	Status	Support	Value/Comment
PME24	For a PHY with a GMII interface the test modes shall be enabled by	40.6.1.1.2	M	Yes [ ]	Setting bits 9:13-15 (1000BASE-T Control Register) of the GMII Management register set as shown in Table 40-7.
PME25	The test modes shall only change the data symbols provided to the transmitter circuitry and shall not alter the electrical and jitter characteristics of the transmitter and receiver from those of normal operation.	40.6.1.1.2	M	Yes [ ]	
PME26	A PHY without a GMII shall provide a means to enable the test modes for conformance testing.	40.6.1.1.2	M	Yes [ ]	
PME27	When transmit test mode 1 is enabled, the PHY shall transmit	40.6.1.1.2	M	Yes [ ]	The sequence of data symbols specified in 40.6.1.1.2 continuously from all four transmitters.
PME28	When in test mode 1, the transmitter shall time the transmitted symbols	40.6.1.1.2	M	Yes [ ]	From a 125.00 MHz $\pm$ 0.01% clock in the MASTER timing mode.
PME29	When test mode 2 is enabled, the PHY shall transmit	40.6.1.1.2	M	Yes [ ]	The data symbol sequence {+2,-2} repeatedly on all four channels.
PME30	When in test mode 2, the transmitter shall time the transmitted symbols	40.6.1.1.2	M	Yes [ ]	From a 125.00 MHz $\pm$ 0.01% clock in the MASTER timing mode.
PME31	When transmit test mode 3 is enabled, the PHY shall transmit	40.6.1.1.2	M	Yes [ ]	The data symbol sequence {+2,-2} repeatedly on all four channels.
PME32	When in test mode 3, the transmitter shall time the transmitted symbols	40.6.1.1.2	M	Yes [ ]	From a 125 MHz $\pm$ 1% clock in the SLAVE timing mode.
PME33	When test mode 4 is enabled, the PHY shall transmit	40.6.1.1.2	M	Yes [ ]	The data symbols generated by the scrambler polynomial specified in 40.6.1.1.2.
PME34	When test mode 4 is enabled, the PHY shall	40.6.1.1.2	M	Yes [ ]	Use the bit sequences generated by the scrambler bits shown in 40.6.1.1.2 to generate the quinary symbols, $s_n$ , as shown in Table 40-8.
PME35	When test mode 4 is enabled, the maximum-length shift register used to generate the sequences defined by this polynomial shall be	40.6.1.1.2	M	Yes [ ]	Updated once per symbol interval (8 ns).

Item	Feature	Subclause	Status	Support	Value/Comment
PME36	When test mode 4 is enabled, the bit sequences, $x0_n$ , $x1_n$ , and $x2_n$ , generated from combinations of the scrambler bits shown in 40.6.1.1.2 shall be	40.6.1.1.2	M	Yes [ ]	Used to generate the quinary symbols, $s_n$ , as shown in Table 40–8.
PME37	When test mode 4 is enabled, the quinary symbol sequence shall be	40.6.1.1.2	M	Yes [ ]	Presented simultaneously to all transmitters.
PME38	When in test mode 4, the transmitter shall time the transmitted symbols	40.6.1.1.2	M	Yes [ ]	From a 125.00 MHz $\pm$ 0.01% clock in the MASTER timing mode.
PME39	The test fixtures defined in Figure 40–22, Figure 40–23, Figure 40–24, and Figure 40–25 or their functional equivalents shall be used for measuring transmitter specifications.	40.6.1.1.3	M	Yes [ ]	
PME40	The test filter used in transmitter test fixtures 1 and 3 shall	40.6.1.1.3	M	Yes [ ]	Have the continuous time transfer function specified in 40.6.1.1.3 or its discrete time equivalent.
PME41	The disturbing signal $V_d$ shall	40.6.1.1.3	M	Yes [ ]	Have the characteristics listed in Table 40–9.
PME42	To allow for measurement of transmitted jitter in MASTER and SLAVE modes the PHY shall provide access to the 125 MHz symbol clock, TX_TCLK that times the transmitted symbols.	40.6.1.1.3	M	Yes [ ]	
PME43	To allow for measurement of transmitted jitter in MASTER and SLAVE modes the PHY shall provide a means to enable the TX_TCLK output if it is not normally enabled.	40.6.1.1.3	M	Yes [ ]	
PME44	The PMA shall	40.6.1.2	M	Yes [ ]	Provide the Transmit function specified in 40.4.2.2 in accordance with the electrical specifications of this clause.
PME45	Where a load is not specified, the transmitter shall	40.6.1.2	M	Yes [ ]	Meet the requirements of this clause with a 100 $\Omega$ resistive differential load connected to each transmitter output.
PME46	The tolerance on the poles of the test filters used in 40.6 shall be $\pm$ 1%.	40.6.1.2	M	Yes [ ]	

Item	Feature	Subclause	Status	Support	Value/Comment
PME47	When in transmit test mode 1 and observing the differential signal output at the MDI using test fixture 1, for each pair, with no intervening cable, the absolute value of the peak of the waveform at points A and B as defined in Figure 40–19 shall fall within	40.6.1.2.1	M	Yes [ ]	The range of 0.67 V to 0.82 V (0.75 V $\pm$ 0.83 dB).
PME48	The absolute value of the peak of the waveforms at points A and B shall	40.6.1.2.1	M	Yes [ ]	Differ by less than 1%.
PME49	The absolute value of the peak of the waveform at points C and D as defined in Figure 40–19 shall differ	40.6.1.2.1	M	Yes [ ]	From 0.5 times the average of the absolute values of the peaks of the waveform at points A and B by less than 2%.
PME50	When in transmit test mode 1 and observing the differential transmitted output at the MDI, for either pair, with no intervening cabling, the peak value of the waveform at point F as defined in Figure 40–19 shall be	40.6.1.2.2	M	Yes [ ]	Greater than 73.1% of the magnitude of the negative peak value of the waveform at point F. Point G is defined as the point exactly 500 ns after point F. Point F is defined as the point where the waveform reaches its minimum value at the location indicated in Figure 40–19.
PME51	When in transmit test mode 1 and observing the differential transmitted output at the MDI, for either pair, with no intervening cabling, the peak value of the waveform at point J as defined in Figure 40–19 shall be	40.6.1.2.2	M	Yes [ ]	Greater than 73.1% of the magnitude of the peak value of the waveform at point H. Point J is defined as the point exactly 500 ns after point H. Point H is defined as the point where the waveform reaches its maximum value at the location indicated in Figure 40–19.
PME52	When in test mode 1 and observing the differential signal output at the MDI using transmitter test fixture 1, for each pair, with no intervening cable, the voltage waveforms at points A, B, C, D defined in Figure 40–19, after the normalization described within the referenced subclause, shall	40.6.1.2.3	M	Yes [ ]	Lie within the time domain template 1 defined in Figure 40–26 and the piecewise linear interpolation between the points in Table 40–10. The waveforms may be shifted in time as appropriate to fit within the template.
PME53	When in test mode 1 and observing the differential signal output at the MDI using transmitter test fixture 1, for each pair, with no intervening cable, the voltage waveforms at points F and H defined in Figure 40–19, after the normalization described within the referenced subclause, shall	40.6.1.2.3	M	Yes [ ]	Lie within the time domain template 2 defined in Figure 40–26 and the piecewise linear interpolation between the points in Table 40–11. The waveforms may be shifted in time as appropriate to fit within the template.

Item	Feature	Subclause	Status	Support	Value/Comment
PME54	When in test mode 4 and observing the differential signal output at the MDI using transmitter test fixture 3, for each pair, with no intervening cable, the peak distortion as defined below shall be	40.6.1.2.4	M	Yes [ ]	Less than 10 mV.
PME55	When in the normal mode of operation as the MASTER; the peak-to-peak value of the MASTER TX_TCLK jitter relative to an unjittered reference shall be	40.6.1.2.5	M	Yes [ ]	Less than 1.4 ns.
PME56	When the jitter waveform on TX_TCLK is filtered by a high-pass filter, $H_{jfl}(f)$ having the transfer function specified in 40.6.1.2.5, the peak-to-peak value of the resulting filtered timing jitter plus $J_{txout}$ , shall be	40.6.1.2.5	M	Yes [ ]	Less than 0.3 ns.
PME57	When in the normal mode of operation as the SLAVE, receiving valid signals from a compliant PHY operating as the MASTER using the test channel defined in 40.6.1.1.1, with test channel port A connected to the SLAVE, the peak-to-peak value of the SLAVE TX_TCLK jitter relative to the MASTER TX_TCLK shall be	40.6.1.2.5	M	Yes [ ]	Less than 1.4 ns after the receiver is properly receiving the data and has set bit 10.13 of the GMII management register set to 1.
PME58	When the jitter waveform on TX_TCLK is filtered by a high-pass filter, $H_{jfl}(f)$ , having the transfer function specified in 40.6.1.2.5, the peak-to-peak value of the resulting filtered timing jitter plus $J_{txout}$ shall be	40.6.1.2.5	M	Yes [ ]	No more than 0.4 ns greater than the simultaneously measured peak-to-peak value of the MASTER jitter filtered by $H_{jfl}(f)$
PME59	For all jitter measurements the peak-to-peak value shall be	40.6.1.2.5	M	Yes [ ]	Measured over an unbiased sample of at least $10^5$ clock edges.
PME60	For all unfiltered jitter measurements the peak-to-peak value shall be	40.6.1.2.5	M	Yes [ ]	Measured over an interval of not less than 100 ms and not more than 1 second.
PME61	The quinary symbol transmission rate on each pair of the MASTER PHY shall be	40.6.1.2.6	M	Yes [ ]	125.00 MHz $\pm$ 0.01%
PME62	The PMA shall provide the Receive function specified in 40.3.1.4 in accordance with the electrical specifications of this clause.	40.6.1.3	M	Yes [ ]	



Item	Feature	Subclause	Status	Support	Value/Comment
PME63	The patch cabling and interconnecting hardware used in test configurations shall be	40.6.1.3	M	Yes [ ]	Within the limits specified in 40.7.
PME64	Differential signals received on the receive inputs that were transmitted within the specifications given in 40.6.1.2 and have then passed through a link compatible with 40.7, shall be translated into	40.6.1.3.1	M	Yes [ ]	One of the PMA_UNITDATA.indicate messages with a 4-D symbol rate error less than $10^{-10}$ and sent to the PCS after link bring-up. Since the 4-D symbols are not accessible, this specification shall be satisfied by a frame error rate less than $10^{-7}$ for 125 octet frames.
PME65	The receive feature shall	40.6.1.3.2	M	Yes [ ]	Properly receive incoming data with a 5-level symbol rate within the range 125.00 MHz $\pm$ 0.01%.
PME66	The signal generator for the common-mode test shall be	40.6.1.3.3	M	Yes [ ]	Capable of providing a sine wave signal of 1 MHz to 250 MHz.
PME67	While sending data from the transmitter the receiver shall	40.6.1.3.3	M	Yes [ ]	Send the proper PMA_UNITDATA.indicate messages to the PCS as the signal generator frequency is varied from 1 MHz to 250 MHz.
PME68	While receiving data from a transmitter specified in 40.6.1.2 through a link segment specified in 40.7 connected to all MDI duplex channels, a receiver shall	40.6.1.3.4	M	Yes [ ]	Send the proper PMA_UNITDATA.indicate message to the PCS when any one of the four pairs is connected to a noise source as described in Figure 40-28.
PME69	The alien crosstalk test specified in 40.6.1.3.4 shall be satisfied by	40.6.1.3.4	M	Yes [ ]	A frame error rate of less than $10^{-7}$ for 125 octet frames
PME70	The noise source shall be	40.6.1.3.4	M	Yes [ ]	Connected to one of the MDI inputs using Category 5 balanced cable of a maximum length of 0.5 m.

**40.12.8 Characteristics of the link segment**

Item	Feature	Subclause	Status	Support	Value/Comment
LKS1	All implementations of the balanced cabling link shall	40.7.1	M	Yes [ ]	Be compatible at the MDI.
LKS2	1000BASE-T links shall	40.7.1	M	Yes [ ]	Consist of Category 5 components as specified in ANSI/TIA/EIA-568-A:1995 and ISO/IEC 11801:1995.
LKS3	Link segment testing shall be conducted using	40.7.2	M	Yes [ ]	Source and load impedances of 100 $\Omega$ .
LKS4	The tolerance on the poles of the test filter used in this section shall be	40.7.2		Yes [ ]	$\pm 1\%$ .
LKS5	The insertion loss of each duplex channel shall be	40.7.2.1	M	Yes [ ]	Less than $2.1 f^{0.529} + 0.4/f$ (dB) at all frequencies from 1 MHz to 100 MHz. This includes the attenuation of the balanced cabling pairs, connector losses, and patch cord losses of the duplex channel.
LKS6	The insertion loss specification shall be met when	40.7.2.1	M	Yes [ ]	The duplex channel is terminated in 100 $\Omega$ .
LKS7	The return loss of each duplex channel shall be	40.7.2.3	M	Yes [ ]	As specified in 40.7.2.3 at all frequencies from 1 MHz to 100 MHz.
LKS8	The reference impedance for return loss measurement shall be	40.7.2.3	M	Yes [ ]	100 $\Omega$ .
LKS9	The NEXT loss between duplex channel pairs of a link segment shall be	40.7.3.1.1	M	Yes [ ]	At least $27.1 - 16.8 \log_{10}(f/100)$ (where $f$ is the frequency in MHz over the frequency range 1 MHz to 100 MHz.)
LKS10	The worst case ELFEXT loss between duplex channel pairs of a link segment shall be	40.7.3.2	M	Yes [ ]	Greater than $17 - 20 \log_{10}(f/100)$ dB (where $f$ is the frequency in MHz) over the frequency range 1 MHz to 100 MHz.
LKS11	The Power Sum loss between a duplex channel and the three adjacent disturbers shall be	40.7.3.2.2	M	Yes [ ]	Greater than $14.4 - 20 \log_{10}(f/100)$ dB where $f$ is the frequency in MHz over the frequency range of 1 MHz to 100 MHz.

Item	Feature	Subclause	Status	Support	Value/Comment
LKS12	The propagation delay of a link segment shall	40.7.4.1	M	Yes [ ]	Not exceed 570 ns at all frequencies from 2 MHz to 100 MHz.
LKS13	The difference in propagation delay, or skew, between all duplex channel pair combinations of a link segment under all conditions shall not exceed	40.7.4.2	M	Yes [ ]	50 ns at all frequencies between 2 MHz and 100 MHz.
LKS14	Once installed, the skew between pairs due to environmental conditions shall not vary	40.7.4.2	M	Yes [ ]	More than $\pm 10$ ns.

#### 40.12.9 MDI requirements

Item	Feature	Subclause	Status	Support	Value/Comment
MDI1	MDI connector	40.8.1	M	Yes [ ]	8-Way connector as per IEC 60603-7: 1990.
MDI2	Connector used on cabling	40.8.1	M	Yes [ ]	Plug.
MDI3	Connector used on PHY	40.8.1	M	Yes [ ]	Jack (as opposed to plug).
MDI4	MDI connector	40.8.2	M	Yes [ ]	A PHY that implements the crossover function shall be marked with the graphical symbol X.
MDI5	The MDI connector (jack) when mated with a balanced cabling connector (plug) shall	40.8.3	M	Yes [ ]	Meet the electrical requirements for Category 5 connecting hardware for use with 100 $\Omega$ Category 5 cable as specified in ANSI/TIA/EIA-568-A:1995 and ISO/IEC 11801:1995.
MDI6	The mated MDI connector and balanced cabling connector shall	40.8.3	M	Yes [ ]	Not have a FEXT loss greater than $40 - 20\log_{10}(f/100)$ over the frequency range 1 MHz to 100 MHz between all contact pair combinations shown in Table 40-12.
MDI7	No spurious signals shall be emitted onto the MDI when the PHY is held in power down mode as defined in 22.2.4.1.5, independent of the value of TX_EN, when released from power down mode, or when external power is first applied to the PHY.	40.8.3	M	Yes [ ]	

Item	Feature	Subclause	Status	Support	Value/Comment
MDI8	The differential impedance as measured at the MDI for each transmit/receive channel shall be such that	40.8.3.1	M	Yes [ ]	Any reflection due to differential signals incident upon the MDI from a balanced cabling having an impedance of $100\ \Omega \pm 15\%$ is at least 16 dB over the frequency range of 2.0 MHz to 40 MHz and at least $10 - 20\log_{10}(f/80)$ dB over the frequency range 40 MHz to 100 MHz ( $f$ in MHz).
MDI9	This return loss shall be maintained	40.8.3.1	M	Yes [ ]	At all times when the PHY is transmitting data or control symbols.
MDI10	The common-mode to differential-mode impedance balance of each transmit output shall exceed	40.8.3.2	M	Yes [ ]	The value specified by the equations specified in 40.8.3.2. Test mode 4 may be used to generate an appropriate transmitter output.
MDI11	The magnitude of the total common-mode output voltage, $E_{cm\_out}$ , on any transmit circuit, when measured as shown in Figure 40-32, shall be	40.8.3.3	M	Yes [ ]	Less than 50 mv peak-to-peak when transmitting data.
MDI12	Each wire pair of the MDI shall	40.8.3.4	M	Yes [ ]	Withstand without damage the application of short circuits across the MDI port for an indefinite period of time without damage.
MDI13	Each wire pair of the MDI shall resume	40.8.3.4	M	Yes [ ]	Normal operation after such faults are removed.
MDI14	The magnitude of the current through the short circuit specified in PME64 shall not exceed	40.8.3.4	M	Yes [ ]	300 mA.
MDI15	Each wire pair shall withstand without damage	40.8.3.4	M	Yes [ ]	A 1000 V common-mode impulse of either polarity ( $E_{cm}$ as indicated in Figure 40-33).
MDI16	The shape of the impulse shall be	40.8.3.4	M	Yes [ ]	0.3/50 $\mu$ s (300 ns virtual front time, 50 $\mu$ s virtual time of half value), as defined in IEC 60060.

**40.12.10 General safety and environmental requirements**

Item	Feature	Subclause	Status	Support	Value/Comment
ENV1	Conformance to safety specifications	40.9.1	M	Yes [ ]	IEC 60950.
ENV2	Installation practice	40.9.2.1	INS:M	N/A [ ] Yes [ ]	Sound practice, as defined by applicable local codes.
ENV3	Care taken during installation to ensure that non-insulated network cabling conductors do not make electrical contact with unintended conductors or ground.	40.9.2.2	INS:M	N/A [ ] Yes [ ]	
ENV4	1000BASE-T equipment shall be capable of withstanding a telephone battery supply from the outlet as described in 40.9.2.3.	40.9.2.3	M	Yes [ ]	
ENV5	A system integrating the 1000BASE-T PHY shall comply with applicable local and national codes for the limitation of electromagnetic interference.	40.9.3.1	INS:M	N/A [ ] Yes [ ]	

**40.12.11 Timing requirements**

Item	Feature	Subclause	Status	Support	Value/Comment
TR1	Every 1000BASE-T PHY associated with a GMII shall	40.11.1	M	Yes [ ]	Comply with the bit delay constraints specified in Table 40-13 for half duplex operation and Table 40-14 for full duplex operation. These constraints apply for all 1000BASE-T PHYs.
TR2	For any given implementation, the assertion delays on CRS shall	40.11.1	M	Yes [ ]	Be equal.
TR3	Every DTE with a 1000BASE-T PHY shall	40.11.2	M	Yes [ ]	Comply with the bit delay constraints specified in Table 40-15.
TR4	To ensure fair access to the network, each DTE operating in half duplex mode shall, additionally, satisfy the following:	40.11.3	M	Yes [ ]	(MAX MDI to MAC Carrier De-assert Detect) – (MIN MDI to MAC Carrier Assert Detect) < 16 Bit Times.

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